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GEOLOGY OF THE PANAMINT SILVER DISTRICT, CALIFORNIA.

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INTRODUCTION.

THIS paper is concerned with the geology of the Panamint mining district, situated in the Panamint Range, southeastern California. The numerous clean-cut silver-bearing fissure veins of this district which occur largely in limestone, have received but slight attention from geologists in the past.[1] The geology of the

[1] Stetefeldt, C. A., Report on Panamint mining district, as quoted by Raymond, R. W., "Mines and Mining in the States and Territories West of the Rocky Mountains for 1875," pp. 33–39, 1877. Fairbanks, H. W., Preliminary report on the mineral deposits of Inyo, Mono, and Alpine counties, Calif. State Mining Bureau, 12th Ann. Rept., pp. 472–478, 1894; "Mineral Deposits of Eastern California," *Amer. Geol.*, vol. 17, pp. 144–158, 1896.

district and the mineralogy of the deposits are relatively simple. There is much conflict in the many more or less indefinite accounts of the extent of production from the several mines, but it seems safe to state that the gross value of the output was over $2,000,000.

The work upon which this paper is based was done in the graduate school of the California Institute of Technology. I am indebted to Dr. F. L. Ransome for the reading of the manuscript of this report and for accompanying me on a brief field trip to the region.

HISTORY OF MINING.

Chalfant[2] states that in 1858 Mormon emigrants found silver ledges in the Panamints and built a small furnace south of the present townsite of Panamint. In about the year 1873 United States Senators John P. Jones of Nevada, and William Stewart of California and Trenor W. Park secured the mining rights on the greater part of the district. It is reported that these rights were procured by purchase from outlaws who previously held and dominated them under some claim, either real or pretended. Numerous companies were organized, but in later years most of them were consolidated into one general company known as the Surprise Valley Mill and Mining Company. During the next few years the town prospered, supporting a population of about 2500 people. A 20-stamp mill and roasting furnace was put into operation in 1875, using some form of pan-amalgamation, probably the Reese River process. Reduction cost amounted to between $18 and $20 per ton. The average assay value of ore delivered to the mill varied from $80 to $100 in silver per ton.[3] Bullion was hauled by 20-mule teams to San Pedro and shipped from there by boat to Swansea, Wales, for smelting. The principal mines developed during this boom period were, in order of importance, Hemlock, Wyoming, and Stewart's Wonder. The year 1877 marked the decline of the district. Since that

[2] Chalfant, W. A., "The Story of Inyo," Pub. by the Author, Chicago, 1922.

[3] Raymond, R. W., "Mines and Mining in the States and Territories West of the Rocky Mountains for 1875," p. 24, 1877.

time mining operations have been intermittent and at the present time consist chiefly of assessment work.

LOCATION AND TOPOGRAPHY.

The Panamint district includes a small area in the immediate vicinity of the abandoned town of Panamint, situated near the head of Surprise Canyon on the western side of the range. It

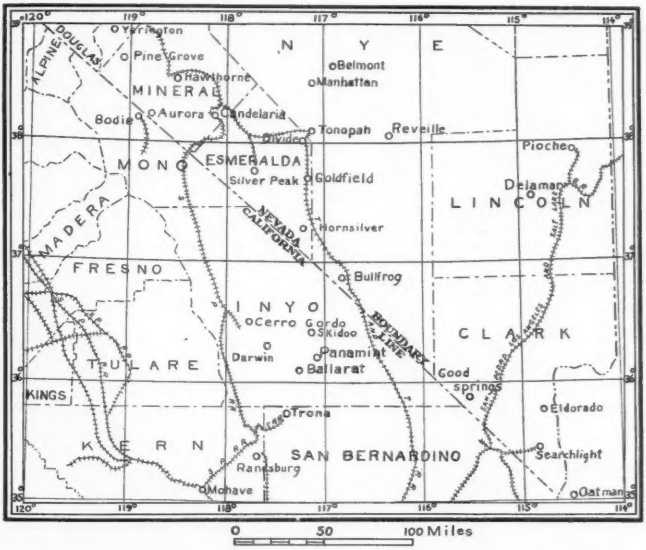


FIG. 1. Index map showing the situation of the Panamint district.

is 11 miles northeast of the almost deserted town of Ballarat, the only settlement in Panamint Valley. A fairly good desert road, 25 miles in length, connects Ballarat with Trona, the nearest railroad point. The geographic setting with respect to other mining districts in Nevada and California is shown in Fig. 1. Numerous scattered mine workings and prospects occur principally to the west, south and southeast of Panamint. The mines of the district nearly all lie in a belt extending about 9,000 feet from east

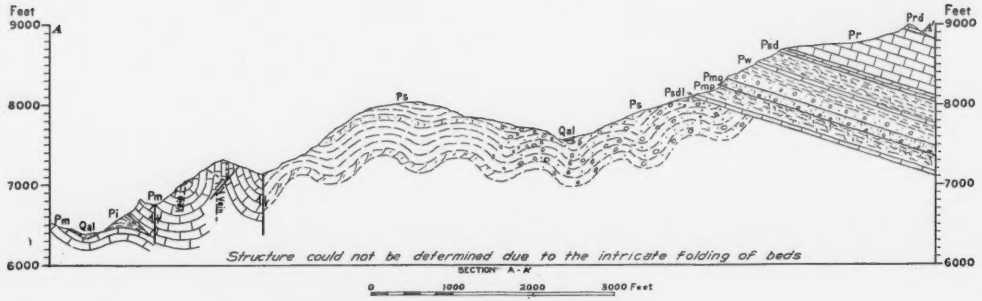


FIG. 2-*A*. Vertical section *A*–*A'* from Fig. 1.

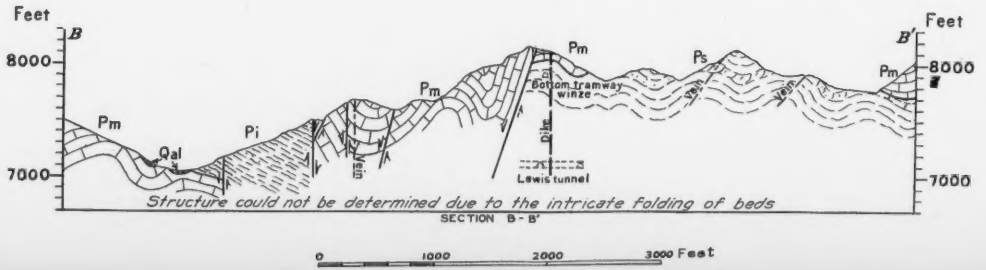
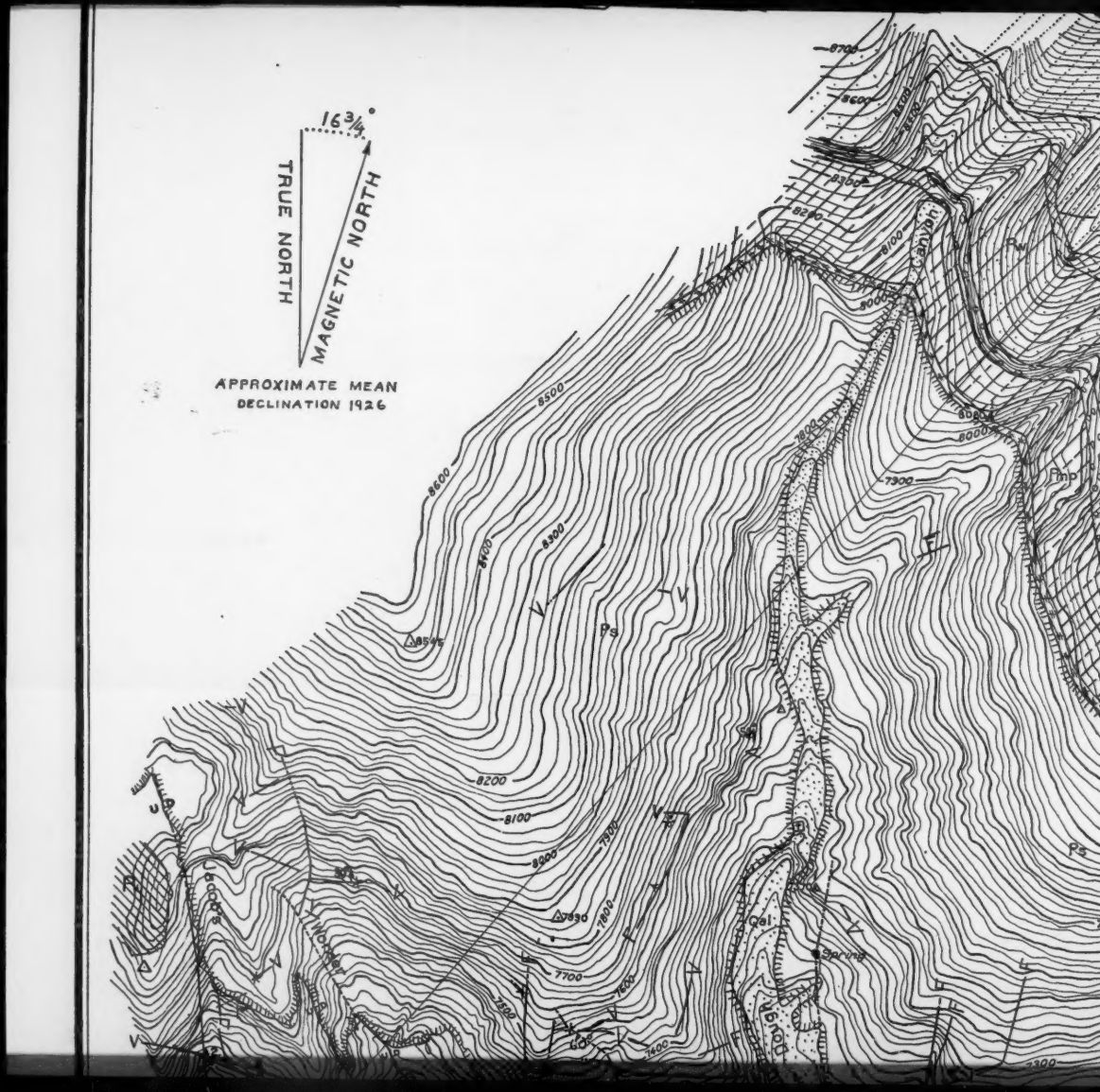


FIG. 2-*B*. Vertical section *B*–*B'* from Fig. 2.

FIG. 2-*B*. Vertical section *B*–*B*′ from Fig. 2.


16 3/4°
TRUE NORTH
MAGNETIC NORTH
APPROXIMATE MEAN
DECLINATION 1926
8700
8600
8500
8400
8300
8200
8100
8000
7900
7800
7700
7600
7500
7400
7300
Pmp
Ps
Qal
Spruce
Aspen
Cabin
Trail

KEY

SEDIMENTARY AND METAMORPHIC ROCKS

QUATERNARY

Qal
Wash and Alluvium

LOWER PALEOZOIC (?)

Telescope group

Prd
Redlands dolomitic limestone

Pr
Radcliff formation

Psd
Sentinel dolomite

Pw
Wildrose formation

Pmg
Mountain Girl Conglomerate-Quartzite

DISCONFORMITY(?)

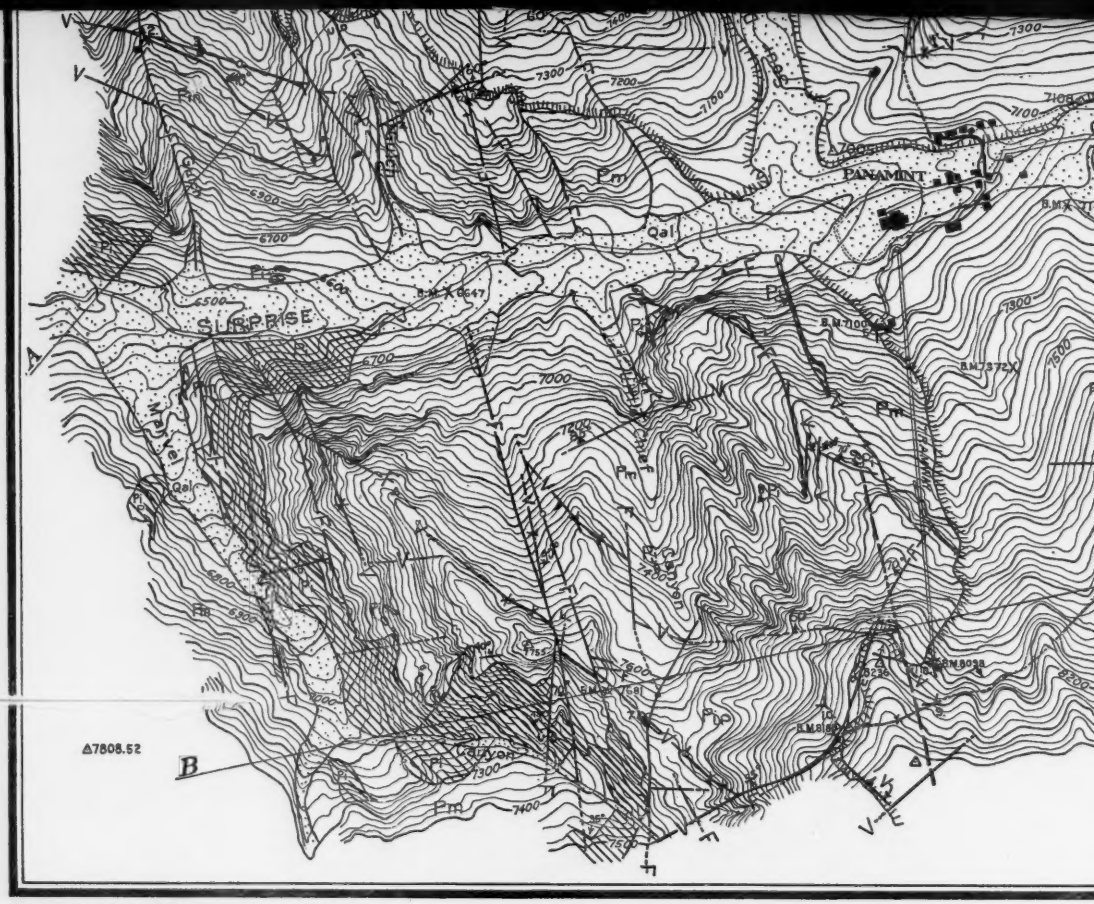
Pmp
Middle Park formation

Psdl
Sour Dough dolomitic limestone

NONCONFORMITY

Ps
Surprise formation

Pm
Marvel dolomitic limestone



Topography by A. P. Patterson and F. Mac Murphy
Control by C. L. Tibbals and F. Percival
Surveyed in 1927

¼ ⅛ 0 ¼ ½ Mile

1000 500 0 1000 2000 3000 Feet

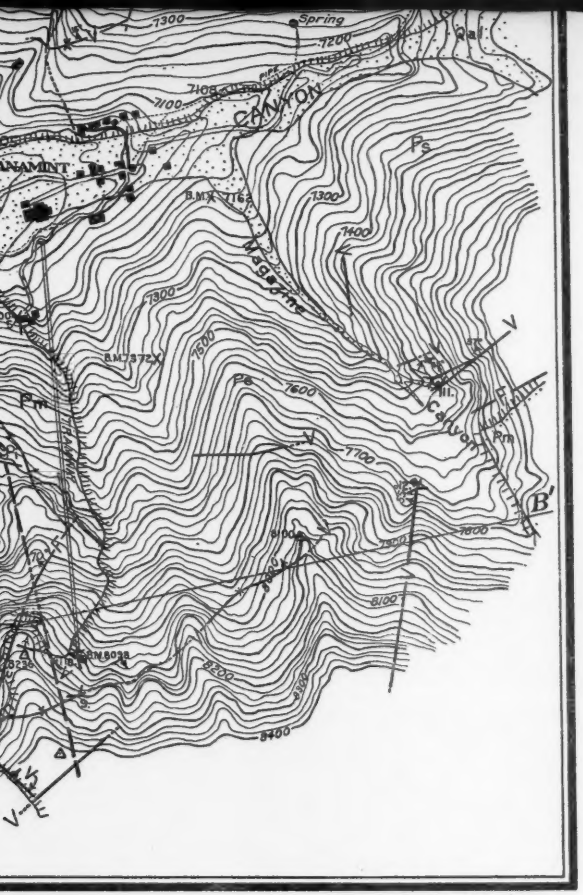
Contour interval 25 feet.

FIG. 2. Geologic map of Panamint mining distri

Note: Geographic position of U. S. Coast and Geodetic Survey's triangulation station "Panamin
one and three-tenths (1.3) miles southerly from Panamint town

Latitude .....
Longitude .....

Datum is 7,100 feet above mean sea level taken from iron pipe at p



Geology by F. Mac Murphy
Surveyed in 1926 and 1927

of Panamint mining district.

ngulation station "Panamint," located on easterly summit Sentinel Peak about
herly from Panamint townsite, is as follows:

..... 36° 05′ 47″.556
.....117° 04′ 35″.970.

taken from iron pipe at portal of Lewis tunnel.

to west and 7000 feet from north to south. The detailed geologic map (Fig. 2) does not embrace the entire district, which extends for some distance south and east of the area mapped.

The Panamint Range is a normal basin-range tilted fault-block approximately 100 miles long, and forms the west wall of Death Valley almost throughout its entire length and the east wall of the somewhat smaller, but very similar, Panamint Valley. The mines are situated well up on the hillsides of a region with strong relief and steep slopes, and the individual mines range in elevation from 7000–8800 feet above sea level (Fig. 3). They are, therefore, opened by adit tunnels. The inaccessibility of the district is augmented by the difficulty of building and maintaining a road in the canyon owing to occasional cloud-bursts or local excessively heavy rains.

THE ROCKS AND THEIR STRUCTURE.

Marvel Dolomitic Limestone.—Most of the veins in the district occur in the Marvel dolomitic limestone. This is essentially a light bluish-gray cherty rock and shows frequent irregular mottling, due to brecciation. Muscovite and tremolite are abundant, an unusual feature in a limestone not very highly crystalline. The bedding is greatly contorted in some places and the rock decidedly schistose. The contact of the Marvel dolomitic limestone with the overlying Surprise formation is nowhere sharply defined and at no place can be called a normal depositional contact. There is usually a gradation from a true limestone to a true schist for a distance of from 5 to 30 feet. The limestone simulates an intrusive relation to the schist, which suggests a squeezing into the less competent layers of the overlying Surprise formation. The very irregular and unusual contact with the Surprise formation is well shown in Fig. 2, although it has here been accentuated to some degree by faulting.

All traces of organic structure have been destroyed. The age of the rock is unknown; from its general characteristics, in part outlined above, a Lower Paleozoic age has been assumed.

The rock is complexly folded to such a degree that bedding has

been almost wholly obliterated and consequently structure could not be determined.

Surprise Formation.—This name is applied to a series of predominantly fine-textured flaggy or slaty rocks which occupy an irregular strip of country on the western side of the Panamint Range. Perhaps the most significant feature is the large number of rock types represented, and there is in consequence a marked change in composition from place to place. They are uninteresting megascopically but rather complex as studied in thin sections under the microscope, and the classification of the various facies rests entirely with the microscope. Due to their fine-grained, compact character, few minerals can be identified by the unaided eye, but approximately 25 metamorphic minerals have been identified in thin sections. The prevailing rock types are: conglomerate-schist, actinolite schist, ottrelite schist, quartz-sericite schist, slate and phyllite, quartz-biotite-tourmaline schist, metamorphosed sandstones and grits, and a relatively few beds of brown limestone. There exist, however, all gradations and combinations of the above very generalized varieties of rocks making up the Surprise formation. Detrital quartz grains were noted in some sections, and although they are ill-sorted and vary widely in size and shape, nevertheless the material may have been uniform in distribution originally. Though bedding is not often seen, it is frequently suggested and there can be no doubt as to their original sedimentary character. The general mineral composition and often slaty character further substantiates this view. It may thus be regarded as a metamorphosed series of sandstones, grits, shales and conglomerate, intercalated with thin limestone beds.

Although in general the schistosity of the rocks strikes N–S and often dips at high angles, yet the angle between directions of schistosity and bedding varies widely from place to place. Frequently, the schistosity is normal to the contact of the Surprise formation with the Marvel dolomitic limestone. The Surprise formation contains rocks of various kinds, but folding, faulting and metamorphism have made it impracticable to recognize any regular stratigraphic sequence.

Telescope Group.--The Surprise formation is separated from the Telescope group of rocks of eight separate units, by a nonconformity. In the Panamint district the following formations have been mapped (Fig. 2): Sour Dough limestone, Middle Park formation, Mountain Girl conglomerate-quartzite, Wildrose formation, Sentinel dolomite, Radcliff formation, and the Redlands dolomitic limestone. The names of these formations are derived from geographic terms used in this part of the Panamint Range. The rocks have nearly all been metamorphosed to some degree and in the absence of diagnostic paleontologic evidence the age of all formations is open to question. Tentative assignment to the Lower Paleozoic has been made largely on lithologic grounds.

The rocks are undeformed and strike N–S with a general dip in this part of the range of 20° eastward.

Little Chief Porphyry.—This rock occurs as a single intrusive body and forms the crest of the range near the head of Surprise Canyon. It is a stock approximately 2 square miles in area and outcrops about a half-mile west of the area mapped. It is intrusive into the Telescope group and may possibly be bounded in part by faults, although this could not be directly ascertained. Beds striking into the granite porphyry have not been deformed. At the irregular granite contact, the alteration has generally produced fine-grained dense siliceous rocks with no megascopic minerals present. Where the granite intrudes limestone, ramifying streaks of chalcedony approaching the variety agate have given the intruded rock a peculiar mottled appearance. Often chalcedony and limestone are arranged in successive layers around a central nucleus.

It is a massive, medium-grained pink rock whose megascopic constituents are orthoclase, plagioclase and quartz, speckled with small black prisms of hornblende. Under the microscope the essential minerals are orthoclase, microcline-perthite, quartz, albite-oligoclase, hornblende and biotite, named in order of apparent abundance. The texture is porphyritic with rather frequent relatively large phenocrysts of microcline-perthite and orthoclase. The groundmass is microgranitic and in some places

micrographic. The pale green, almost colorless hornblende, occurring in relatively small idiomorphic crystals, is a rather unusual mineral of the rock. It is characterized by streaks of brown that have probably resulted from leaching. Apatite, magnetite, titanite and muscovite are accessory minerals.

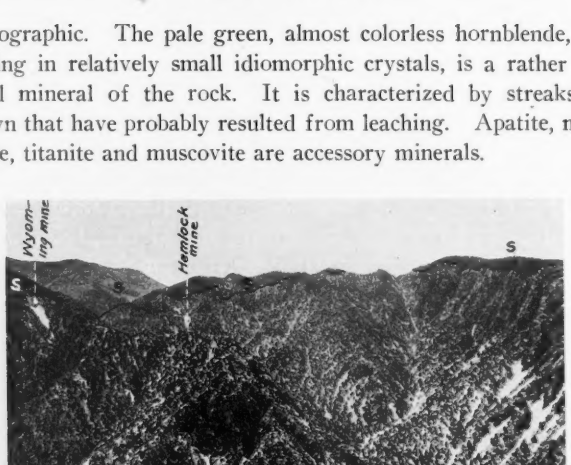


FIG. 3. View south from near Camp Bird Mine looking up Marvel Canyon, showing the rugged topography of the intricately folded and faulted Marvel dolomitic limestone in the Panamint district. The Surprise Canyon road shows in the lower center. *S*, Surprise formation; *a*, schist interbedded with the Marvel dolomitic limestone.

Dikes.—Hornblende-diorite porphyry dikes cut Marvel dolomitic limestone, Surprise formation and the rocks of the Telescope group. They were intruded subsequent to the folding of the Marvel dolomitic limestone and the Surprise formation. They are older than the veins and in a few places have been cut by them. The dikes are rather inconspicuous, varying in width from 2 to 15 feet with an average of about 5 feet. They have a general strike of from N–S to NW–SE and dip from 70° to vertical. Many of them are continuous for a distance of nearly

a mile. One of these dikes was distinguished in the mapping as an aid in the solution of a fault problem in connection with the Wyoming vein.

The color of the freshly fractured rock is olive green. Prisms of hornblende are not always seen, but when present is the only mineral visible to the naked eye. Its decomposed character prevents its being classified satisfactorily. The groundmass is holocrystalline and consists essentially of hornblende and plagioclase. The prevailing green color of the rock has resulted from the epidotization of the feldspar. Augite is present in some sections. Clinozoisite, biotite, chlorite and interstitial quartz are secondary minerals.

Faulting.—The post-mineral fissures which dislocate many of the veins in the district generally have a N–NW by S–SE trend. As a rule dips are high. They are normal faults of small vertical displacement and small horizontal offset. A notable and characteristic feature of these faults is the deposition of travertine in banded layers cementing the actual fault plane or the large and small blocks of limestone or schist which have been torn loose in the faulting. Many of them are in effect veins of travertine. The faults are largely confined to the Marvel dolomitic limestone and many of them are difficult to trace far beyond the limestone-schist contact. Post-mineral movement has occurred along a few of the fissure veins. The Stewart's Wonder vein has been brecciated by post-mineral movement, in some places along both the footwall and hanging wall.

ORE DEPOSITS.

Quartz-Galena-Pyrite Veins.—These veins usually occur in schist and in some instances follow directions of schistosity. The contact veins which often follow either the lower or upper contacts of the Sour Dough limestone are of this type. They carry coarse grained galena, with subordinate pyrite, chalcopyrite and zinc blende. Tetrahedrite was observed in a few polished sections. In a few places where the veins have been worked, the ore is valuable chiefly for lead, with subordinate silver. The

silver is apparently contained in the galena. The order of deposition of the minerals is generally as follows: pyrite, sphalerite, chalcopyrite, and galena.

Pyrrhotite-Pyrite-Quartz Veins.—Veins of pyrrhotite-pyrite-quartz composition are here treated separately. They are entirely different in character from the other veins in the district, and their mineral assemblage is of some geologic interest. They outcrop about a half a mile northeast of Panamint townsite and just outside the area included on the geologic map (Fig. 2). The veins occur in schist and the principal one, known as the Kern prospect, strikes roughly N. 40° W. and dips 25° NE., apparently following the schistosity of the schist. The ore is said to range in tenor from $13 to $17 per ton in gold.

The Kern vein, whose average width is 2 feet, is heavily mineralized and the typical ore is composed almost wholly of pyrrhotite, pyrite, marcasite with subordinate coarsely granular glassy quartz. The sulphides impregnate the wall rock for a distance of several inches from the vein. Examination of several specimens of massive pyrrhotite ore in reflected light showed the development of marcasite closely associated with siderite. The marcasite possesses the usual characteristic properties ascribed to this mineral and almost invariably shows concentric rings; but its identity was fixed by the rotation of the plane of polarization of reflected light. The carbonate was identified under the petrographic microscope. It has a high index of refraction and an ashen-gray color with distinct absorption, which, according to Winchell [4] is especially characteristic, although not pronounced. The chemical properties also closely conform to those of siderite.

Siderite appears to be both contemporaneous with and later than marcasite. Though it is often concentric with the structure of the marcasite and fills the spaces between successive rings, yet it frequently forms veinlets which cut across the marcasite. Veinlets of siderite, associated with a few widely scattered grains of quartz, are commonly bordered by colloform marcasite, as

[4] Winchell, A. N., "Elements of Optical Mineralogy," Part II., p. 79, New York, 1927.

shown in Fig. 4, *A*. Again marcasite replaces pyrrhotite along apparent cleavage or crystallographic directions which expand into more or less globular shaped masses built up of concentric shells (Fig. 4, *B*).

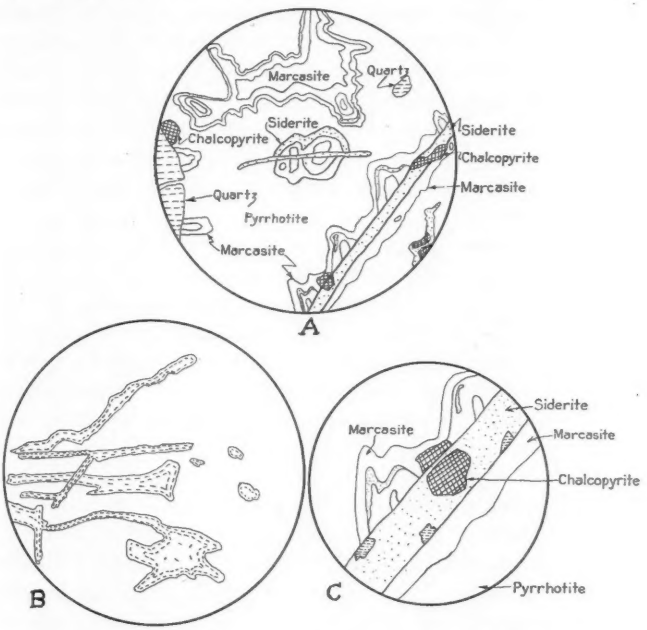


FIG. 4. Drawings of polished surfaces of ores from the Kern Prospect.

A shows relations between pyrrhotite (white), marcasite, chalcopyrite (cross-lined), siderite (dotted) and quartz (broken-lined). × 12.

B. Replacement of pyrrhotite by marcasite along fairly definite directions but commonly expanding into globular masses built up of concentric shells. × 12.

C shows relations between pyrrhotite (white), marcasite, chalcopyrite (cross-lined), siderite (dotted), and quartz (broken-lined). × 36.

Chalcopyrite is commonly associated with the siderite veinlets and was probably contemporaneous with and earlier than siderite. Occasional veinlets of siderite, usually of such dimensions as to

be noticed only under high magnification, cut entirely through grains of chalcopyrite. Chalcopyrite cuts across the structure of the marcasite, which suggests but does not prove replacement. The relations above mentioned are shown in Fig. 4, *C*.

Pyrite is replaced by an intricate network of quartz veinlets. However, the relations of pyrite to the other minerals in the deposit could not be ascertained with certainty. Gold was not observed in polished sections of the ore. On the assumption that there has been a single generation of quartz, the order of deposition appears to be as follows: pyrite, quartz, pyrrhotite, chalcopyrite, marcasite, and siderite overlapping with the marcasite and the chalcopyrite.

The occurrence of marcasite replacing pyrrhotite and the development of a carbonate, particularly a sideritic carbonate, both contemporaneous with and later than marcasite, has recently been mentioned by several observers.[5] The facts seem to indicate that the marcasite may have either a supergene or hypogene origin in the several occurrences discussed by Newhouse. The assigning of a hypogene origin for the marcasite was based largely on the fact that quartz was deposited later than marcasite and that supergene sulphide deposition is only rarely accompanied by quartz.

Oxidation products are almost entirely lacking in the ores from the Kern prospect. The sulphides occur at the surface and pyrrhotite has not been noticeably oxidized to limonite. In the silver-bearing veins to be described, the zone of oxidation is shallow and commonly the sulphides occur at the surface. Moreover, there is little indication of supergene enrichment in the silver ores of the district. In the massive sulphide ore from the Kern prospect there is certainly no reason for assuming a supergene origin for the chalcopyrite. It seems improbable, therefore, that

[5] Gilbert, G., "Oxidation and Enrichment at Ducktown, Tenn.," *Trans. A. I. M. M. E.*, No. 1318, pp. 998–1023, 1924.

Newhouse, W. H., "Paragenesis of Marcasite," ECON. GEOL., vol. 20, pp. 54–66, 1925.

Tolman, Jr., C. F., and Rogers, A. F., "Study of the Magmatic Sulfid Ores," p. 40, Leland Stanford Univ. Ser., 1916.

Buddington, A. F., U. S. Geol. Survey Bull. 773, p. 104, 1925.

Note: Carbonate does not occur in the deposit described by Buddington.

marcasite was deposited by supergene solutions, and a hypogene origin is favored.

Another gold deposit, the Mountain Girl mine, is situated at the head of Happy Canyon and about 4 miles in an air line south of Panamint townsite. There are a considerable number of small quartz veins on the property which in some instances follow the jointing of the conglomerate-schist country rock. The metallic minerals of hypogene origin include, in the approximate order of their abundance, pyrrhotite, arsenopyrite, chalcopyrite, pyrite, and coarse gold. Commonly pyrrhotite has been metasomatically developed in the wall rocks adjacent to the veins and always as a replacement, either in whole or in part, of quartzite fragments of the country rock. The gangue is massive, glassy, coarsely crystalline quartz associated with subordinate siderite.

A characteristic feature of the deposit is the occurrence of coarse gold at the junction of calcite stringers with quartz veins (Fig. 5). These stringers are rarely over a hairbreadth in thick-

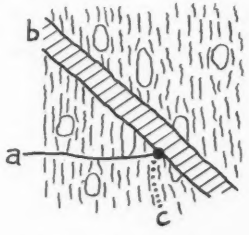


FIG. 5. Sketch plan showing the occurrence of coarse gold at the junction of a calcite stringer with a quartz vein. *a*, calcite stringer; *b*, quartz vein; *c*, gold. The rock is conglomerate schist.

ness but may attain a width of 1/16 of an inch. Usually they join the vein at an acute angle and apparently are confined to the footwall side. The stringers are seldom traceable into the country rock for a distance of over 2 feet. The general occurrence of coarse gold at the junction of calcite stringers with quartz veins was noted, and this suggests a dependent relationship.

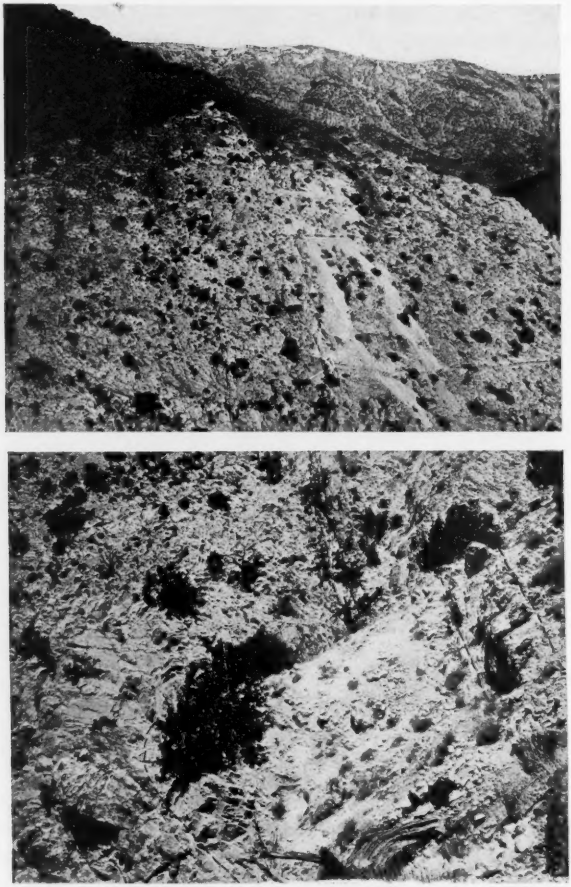


FIG. 6. *A*, (above) Looking east across Wonder Gulch, showing displacement along the Stewart's Wonder vein. The light rock in the foreground is the Marvel dolomitic limestone and the dark rock the Surprise formation. The background is occupied by the Little Chief porphyry.

B. (below) Near view of the Stewart's Wonder and Rainbow veins as exposed on ridge just east of Jacob's Gulch. The Rainbow vein (left) dips 40° north and intersects the vertical Stewart's Wonder vein. The quartz of each vein is here about 6 feet wide. The continuation of the Stewart's Wonder vein west of Jacob's Gulch is outlined by dashed lines. The country rock is the Marvel dolomitic limestone.

Silver-bearing quartz veins.

Distribution, Form, and Structure.—The occurrence of numerous, strong, continuous and clean-cut quartz veins is the most interesting feature of the district. They vary considerably in

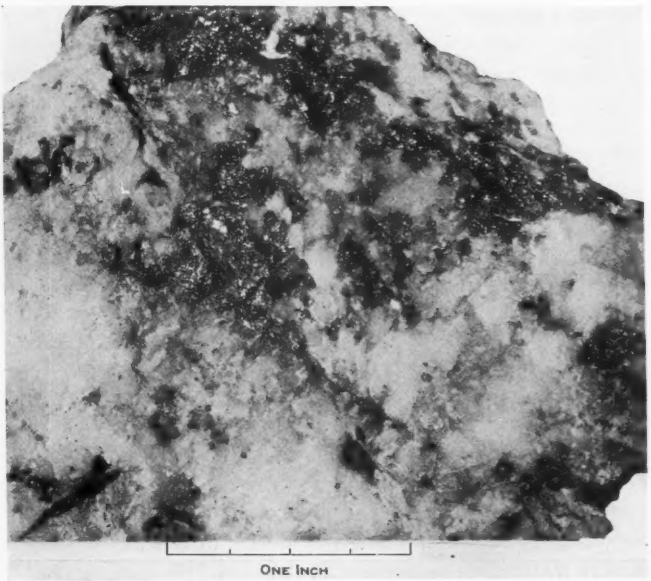


FIG. 7. Typical hypogene silver ore from the Panamint district. Quartz (light), and sulphides, chiefly tetrahedrite (dark), Wyoming mine.

width from mere stringers up to those 25 feet wide, and average perhaps 6 feet. The outcrops are well exposed naturally and are easily traceable, some for a distance of over a half a mile. They traverse both the Surprise formation and the Marvel dolomitic limestone but those in the limestone are more numerous and do not vary greatly in width from place to place along the strike.

Undoubtedly this is because the limestone was more easily fractured than the schist. The veins follow fractures whose strikes vary within rather wide limits but the larger number of them have a general northwesterly or northeasterly trend. As a rule dips are steep, ranging usually from 55° to vertical. The most prominent and productive veins are the Hemlock, Wyoming and Stewart's Wonder.

Whereas the structure of the veins is generally decidedly massive, in places rude indistinct banding was noted but in no way does it resemble the delicate concentric banding of the epithermal deposits. The contact between quartz and both foot and hanging walls is sharp and seldom accompanied by gouge. There is little if any alteration of the wall rock, and the mineralization never extends into the country rock. No suggestion of dolomitization was observed.

The structure of the ore is massive and the sulphides are irregularly distributed within the quartz, with generally no relation to either the foot or hanging walls of the veins. The ore shoots are small and of pockety character. Quartz druses occur but are relatively few in number. Many of them appear to be related to planes approximately parallel to the walls. They are unfilled portions of the veins and are generally lined with large quartz crystals.

Mineralogy of the Ores.—The principal and almost exclusive vein filling is milk-white, or glassy quartz of coarsely crystalline massive texture. The quartz is decidedly of the mesothermal or hypothermal variety. Microscopically, where undeformed after deposition, the quartz has a hypidiomorphic granular texture. This is well shown in Fig. 8, *B*. Although much of the quartz is undeformed, it may show cataclastic effects from undulatory extinction to granulation of the large grains. The quartz contains very fine inclusions which commonly give it an almost kaolinized appearance in ordinary light. Calcite and possibly ankerite, occur only sparingly as vein minerals and are rarely observed except under high magnification. They replace or fill fractures in quartz. White tabular crystals of barite were ob-

served in one specimen of ore and this is contemporaneous with or later than quartz.

The metallic minerals of undoubted hypogene origin include, in the approximate order of their abundance, tetrahedrite, galena, sphalerite, pyrite and chalcopyrite. In the silver ores of the district, the silver is almost wholly contained in the tetrahedrite (freibergite). This is the principal sulphide mineral. The mineral usually gives qualitative reactions for both arsenic and antimony. Rather coarsely cleavable galena and light brown sphalerite are important minerals in the typical ore. Large areas

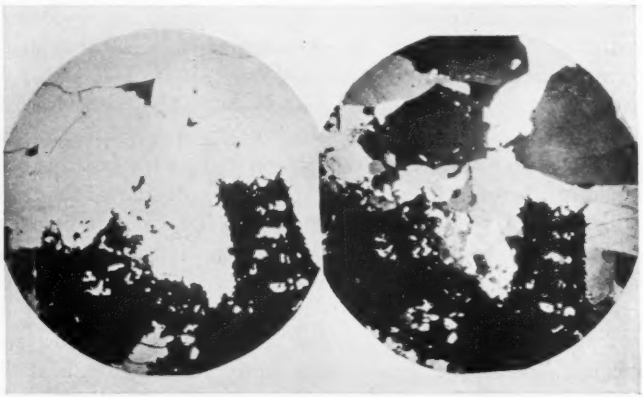


FIG. 8. Photomicrographs of ores.

A (left) Typical sulphide ore from the Panamint district, showing sulphides (black) in part filling open spaces between large undeformed quartz grains, in part filling irregular cracks in fractured quartz, and in part replacing brecciated quartz. The sulphides consist chiefly of tetrahedrite. Ordinary light. × 15.

B (right) Same as *A*. Nicols crossed, showing coarsely granular texture of quartz with partial development of idiomorphic forms.

of galena generally contain a number of good-sized rounded spots of tetrahedrite. Pyrite and chalcopyrite are rarely seen in the hand specimen, though small grains may be seen in polished surfaces under the microscope.

Paragenesis.—A regular sequence of deposition of the hypogene minerals was difficult to obtain for the various veins in the district as a whole. There appears to have been a slight overlapping but the order generally applying is as follows: pyrite, sphalerite, tetrahedrite and galena. The relations existing between chalcopyrite and the other minerals is largely unknown, owing to the scarcity or absence of this mineral in all specimens examined. However, chalcopyrite is replaced by galena.

The impression conveyed in a microscopic study of the ores is that the quartz is earlier than all the sulphides. In some instances replacement has taken place around the borders of large idiomorphic quartz grains, in others it has replaced brecciated quartz, and again it may fill open spaces between large undeformed quartz grains.

Oxidation and Supergene Enrichment.—The physiographic history of the region indicates that after the formation of the veins they were subject to deep erosion in Tertiary time. There would be, therefore, opportunity for the formation of zones of oxidation and supergene enrichment. Water has not been encountered in any of the mines. The ruggedness of the topography and comparative sparseness of vegetation favor a quick run-off. The speed of erosion has probably exceeded that of oxidation. Consequently, the zone of oxidation is shallow and irregular, and frequently almost unaltered sulphides occur at the surface. Oxidized ores have yielded only a comparatively small part of the total production of the district. The irregularity of the oxidized ores depends more on the permeability of the vein at any particular place than on the depth below the surface. Where the veins have been followed by post-mineral fissures with perhaps shattering of the quartz itself, the degree and extent of oxidation is naturally much greater. The almost entire absence of pyrite in the ores was unfavorable for oxidation and supergene enrichment processes.

The metallic minerals of the oxidized ores include malachite, azurite, anglesite, cerusite, smithsonite, bindheimite and cerargyrite. Bindheimite is a rare constituent of the oxidized ores of a few of the mines in the district. It is soft, ocherous material

of a yellow to yellowish-green color. It usually occurs with tetrahedrite, galena and malachite. The mineral has probably resulted from the oxidation of tertahedrite. Very probably the antimony is furnished by the tetrahedrite and the lead by the galena similar to many of the Idaho occurrences.[6] Galena oxidizes to anglesite and cerusite. One specimen of ore from the dump of the Little Molly prospect showed nodules of lead sulphide surrounded by dark concentric shells of lead sulphate, which in turn are surrounded by shells of lead carbonate. Sphalerite alters to smithsonite but the latter mineral is nowhere abundant in the Panamint ores. Cerargyrite also occurs subordinately.

The minerals that strongly suggest deposition by supergene waters are stromeyerite, chalcocite, and covellite. In all the specimens examined they are present only in very subordinate amount. Sphalerite is characteristically replaced by incipient veinlets of chalcocite and infrequently bordered by thin coatings of chalcocite. This fact is rarely brought out except under high magnification. Tetrahedrite is also partially replaced by chalcocite in tiny veinlets that frequently rim large and small areas of tetrahedrite along the borders of quartz grains. Covellite forms veinlets in sphalerite but more commonly occurs as small blebs in galena or in veinlets crossing galena areas that appear to follow crystallographic or cleavage directions. The only later rich silver mineral definitely identified is stromeyerite. This mineral replaces tetrahedrite in a complex system of small veinlets and is generally associated with chalcocite.

Origin and Age of the Deposit.—Although the veins occur along fissures that have been produced by normal faulting, these, as is generally the case, are not structurally important faults and in only one instance show measurable displacement. Owing, however, to the lack of regular bedding planes and horizon markers, some of the fissures along which the veins run may have suffered more displacement than is at first evident.

A likely explanation of banding is that the veins have been

[6] Shannon, Earl V., "The Minerals of Idaho," U. S. Nat. Mus. Bull. 131, p. 435, 1926.

formed by successive small enlargements of the fissures rather than from the subsequent shearing of the veins. A further suggestion of banding has in some cases resulted from included fragments of wall rock.

The ores have been deposited in open spaces in favorable places in the veins, and have not replaced the adjacent wall rocks. Although undoubtedly replacement has taken place in the more minutely shattered country rock, the veins would correspond to the old definition of "true fissure veins." The veins in limestone are interesting in that replacements has been a subordinate factor in their development.

Whereas the veins do vary somewhat in mineral composition, they are all of the same general type and the vein filling was probably contemporaneous over the district as a whole. The evidence afforded by the exposed junction of the Stewart's Wonder and Rainbow veins warrants this conclusion, but other supporting facts are not available.

The mineral deposits are like those that have been generally considered elsewhere to have been deposited by ascending hot waters. The source of the solutions is not known, but it seems most probable that the ores are genetically related to the deeper rock masses that supplied the material for the intrusion of the Little Chief porphyry. Such a relation is suggested but definite proof is not available. The Little Chief porphyry is the only body of an igneous rock in the vicinity of the district. The age of the intrusion is not known aside from the fact that it intrudes rocks of supposed Paleozoic age. Judging solely from the general character of the veins and their mineral constituents, particularly the massive milk-white coarsely crystalline quartz, the ores were probably formed during the late Mesozoic metallogenetic epoch following the intrusion of the granite porphyry.

GENERAL SUMMARY.

1. The occurrence of numerous clean-cut silver-bearing quartz veins is described. They outcrop in limestone, schist or slate but those in the limestone are more numerous and persistent.

2. The principal and almost exclusive vein filling is milk-white sometimes glassy quartz of coarsely crystalline massive texture. The sequence of deposition of the hypogene minerals is pyrite, sphalerite, tetrahedrite, and galena. The silver is almost wholly contained chemically bound in the tetrahedrite, the principal sulphide mineral.

3. Oxidation and supergene enrichment products are not abundant in the ores, but the following minerals have been identified: malachite, azurite, anglesite, cerusite, smithsonite, bindheimite, cerargyrite, stromeyerite, chalcocite, and covellite.

4. The ores have been deposited in open spaces in favorable places in the veins and have not replaced the adjacent wall rocks to any noticeable extent. The veins are generally quite barren and the ore shoots are small and of pockety character.

5. The deposits are classified as those formed at intermediate depths and suggest a genetic relationship with an intrusion of granite porphyry.

6. An unusual vein in the district carries, in order of deposition, pyrite, quartz, pyrrhotite, chalcopyrite, marcasite, and siderite, the latter overlapping with marcasite and chalcopyrite.

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STUDY OF THE BLACK SHALE OVERLYING THE CAP ROCK OF THE CROMWELL SAND IN RELATION TO THE ORIGIN OF THE CROMWELL OIL DOME, OKLAHOMA.[1]

OLIVER R. GRAWE.

INTRODUCTION.

THE Cromwell dome is one of many similar oil-bearing structures in the Mid-Continent region. It is located in T. 10 N., R. 8 E. and T. 11 N., R. 8 E., northeastern Seminole and adjacent Okfuskee Counties, Oklahoma. It contains an area of 4,700 acres and includes two villages, Cromwell City and Struggleville.

The first well in the area was completed by the Cosden Oil and Gas Company on November 11, 1922. It yielded gas under high pressure, but no oil. Nearly a year later, October 2, 1923, a company headed by Joe I. Cromwell drilled into a sand 3,467 to 3,495 feet below the surface and obtained an initial daily production of 350 barrels of 39°Bé. oil which flowed naturally under the high gas pressure.[2] This pay sand was called the Cromwell sand and the field became known as the Cromwell Pool.

THE PROBLEM.

The present petrographic investigation of the black shale overlying the cap rock of the Cromwell sand was undertaken as part of the Cromwell Project of the Committee on Studies in Petroleum Geology of the National Research Council.[3] The project

[1] Part of a thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Graduate College of the State University of Iowa, August, 1927.

[2] Rison, C. O., and Bunn, J. R., "Petroleum Engineering in the Cromwell Oil Field," Mid-Continent Oil and Gas Assoc. Year Book, 1924, p. 5.

[3] Committee on Studies in Petroleum Geology, "Cromwell Project," Report of the Division of Geology and Geography of the National Research Council, April 25, 1925, Appendix, Exhibit F.

was conceived and financed by James H. Gardner, who had samples of well cuttings collected in order to "discover if the folding in the Cromwell field is due to yielding to regional stress at a point of weakness, or to the application of excessive stress at a point which is not necessarily weaker than the surrounding territory." [4]

The suites of samples collected by Mr. Gardner made possible four independent investigations of the problem:

1. A study of the Cromwell sand.
2. A study of the cap rock.
3. A study of the black shale overlying the cap rock.
4. A study of the limestone a short distance above the cap rock.

The oil sand itself and the limestone above the black shale have not been examined. The cap rock has been studied by Somers,[5] who found petrographic evidences of faulting but drew no conclusions regarding the origin of the folded structure.

The specific purpose of the present investigation is to determine the variations in composition and in properties of the black shale overlying the cap rock in order to discover if the Cromwell dome is the result of regional or of local forces. If excessive local pressure caused the doming, as suggested by Gardner,[6] the shale near the top of the structure should be metamorphosed more than that on the flanks, whereas, if the folding is due to regional stress, no such effects should be observed.

METHOD OF SAMPLING.

Cable tool cuttings of the shale in the southern part of the field were obtained by Mr. Gardner and were forwarded to the writer by K. C. Heald. Most of the samples contain fragments of indurated sandstone cap rock from which the shale had to be separated by sieving and hand picking. The depth at which each sample was obtained was determined with a steel line. These

[4] *Idem.*

[5] Somers, R. E., "Petrographic Criteria of Structure in the Cromwell Oil Field, Oklahoma," ECON. GEOL., vol. 23, 1928, pp. 317–322.

[6] Gardner, J. H., "Rock Distortion on Local Structures in the Oil Fields of Oklahoma," *Bull. Am. Assoc. Petrol. Geol.*, vol. 6, 1922, pp. 228–243.

measurements and the association of the cap rock with the shale constitute evidence sufficient to indicate that the samples came from a single horizon, namely, the contact of the shale and cap rock. Therefore, any difference in composition or in properties of the shale are to be interpreted as horizontal rather than as vertical variations.

STRATIGRAPHY.

The exact stratigraphic position of the shale is questionable. Rison and Bunn [7] expressed the opinion prevalent during the early drilling of the field that the Cromwell sand represents part of the Dutcher series of Pottsville age. Powers [8] and Levorsen [9] correlated the cap rock with the Pitkin formation of the Chester series but Levorsen [10] later changed his view and correlated the limy cap rock of the Cromwell sand with the Morrow and Wapanuka limestones, stating that the Cromwell sand itself is basal Pottsville and approximately equivalent to the productive Bend horizon of Texas. This is essentially the correlation given by Rison and Bunn and accepted by Somers.[11] If the Cromwell cap rock is the local representative of the Morrow and Wapanuka formations, then the horizon above the cap rock must be the base of the Atoka formation.

STRUCTURE.

The structure of the shale is essentially that of the top of the cap rock of the Cromwell sand. A map depicting the generally accepted idea of the structure at this horizon as interpreted from well logs has been published by Somers [12] and is reproduced here as Fig. 1. The general structure is an anticline approximately

[7] Rison, C. O., and Bunn, J. R., *op. cit.*, p. 5.

[8] Powers, Sidney, "Petroleum Geology in Oklahoma," Oklahoma Geol. Survey, Bull. 40–G, 1926, p. 18.

[9] Levorsen, A. I., "Convergence Studies in the Mid-Continent Region," *Bull. Am. Assoc. Petrol. Geol.*, vol. 11, 1927, Fig. 1, p. 568, Fig. 2, p. 661.

[10] Levorsen, A. I., "Geology of the Seminole County," Oklahoma Geol. Survey, Bull. 40–BB, 1928, pp. 17, 18, 30, and 43.

[11] Somers, R. E., *op. cit.*, p. 317.

[12] Somers, R. E., *op. cit.*, p. 318.

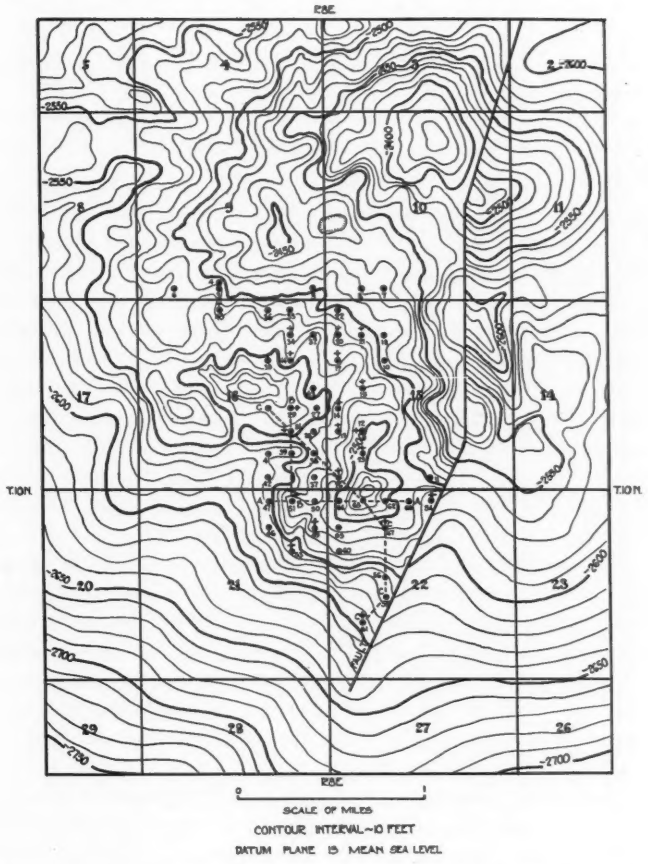

FIG. 1. Structure contour map of top of Cromwell cap rock, southern part of Cromwell Oil field, Oklahoma. After R. E. Somers.

nine miles long and five miles wide trending slightly west of north and east of south. It is superimposed upon a homocline which has a general west dip of less than one degree. The major structure is modified by several minor domes and basins and by several en echelon faults which cut the east limb of the fold.

LITHOLOGY.

The shale appears black on fresh surfaces but the usually observed bruised or chaffed surface presents the color of the streak, a mat neutral gray. Lithification has progressed far enough so that the rock fulfills the requirements of a shale as defined by Lewis.[13] It is a very fine-grained, slaty rock with splintery fracture. Fissility is well developed so that fragments can be easily cleaved parallel to the bedding. Fresh cleavage surfaces possess a characteristic luster due to the reflection of light from minute mica flakes set in the mat groundmass. The hardness is between 2 and 2.5. The rock checks in water but does not break down completely. After surface powder has been washed away, the clean shale no longer renders water muddy. These properties are characteristic of the shale throughout the structure.

The possibility of using lithologic character of shale as an index of metamorphism in regions where coal beds are absent has been suggested by Wilson.[14] In his study of the Cretaceous shales associated with coal in the Rocky Mountain states, Wilson correlates such properties as those possessed by the shale overlying the Cromwell cap rock with a degree of metamorphism sufficient to produce 60 per cent. fixed carbon in coal. Such a degree of metamorphism has been found to be highly unfavorable to commercial petroleum production[15] and Wilson lists several fields which contain shales having the above properties and which have produced little or no oil. He points out, however, that before lithologic properties of shale can be used as criteria of

[13] Lewis, J. V., "Fissility of Shale and Its Relations to Petroleum," *Bull. Geol. Soc. Am.*, vol. 35, 1924, p. 568.

[14] Wilson, J. H., "Lithologic Character of Shale as an Index of Metamorphism," *Bull. Am. Assoc. Petrol. Geol.*, vol. 10, 1926, pp. 625–633.

[15] White, David, "Some Relations in Origin between Coal and Petroleum," *Wash. Acad. Sci. Jour.*, vol. 5, 1915, pp. 189–212.

metamorphism, they must be known in regions where the shale is associated with coal having less than 60 per cent. fixed carbon. It is the importance of this knowledge which the present writer wishes to emphasize, for the correlation which Wilson found between the properties of shale and the production of certain western fields is not applicable to the Cromwell Pool, a field which produced a total of 30, 595, 330 barrels of oil up to July 1, 1927.

MICROSCOPY.

Ten thin sections representative of the shale along two lines of cross-section, A–A and B–B (Fig. 1), together with many others were examined under a petrographic microscope. No mineralogic or textural variations in accord with the structure were detected. The shale on the flanks of the fold is identical with that on the crest. The principal petrographic features are embodied in the following description.

The exceedingly fine grain of the shale limits the means of determining its component minerals. Approximately 50 per cent. of the rock is beyond the resolving power of the petrographic microscope and the largest particles are grains and slivers of structureless organic matter having a maximum length of 0.1 mm. and an average dimension of less than 0.02 mm. They are decidedly black and coaly, appearing brownish only in the thinest sections or in colloidal aggregates well disseminated through the inorganic matrix. Organic matter constitutes about one per cent. of the rock, far less than one would estimate from the blackness of the massive specimen.

Approximately 15 per cent. of the determinable inorganic matter is quartz. A few grains are rounded and as large as 0.1 mm. but most of them are angular and have a maximum dimension of less than 0.005 mm. They are readily identified by their low refringence, weak birefringence and particularly by their characteristic " wink " on rotation under crossed nicols. None of the grains exhibits secondary enlargement but the small angular grains exhibit wavy extinction. Since this phenomenon is confined to the smaller grains, it may be due to the successive extinction of several grains in an aggregate. If it were due to

strains set up during the folding and metamorphism of the shale, the well rounded grains would exhibit this phenomenon also.

Mica, probably in the form of sericite, is an important constituent of the shale, forming approximately 25 per cent. of the rock. Fragments of the shale have a micaceous appearance, the mica flakes reflecting points of light in strong contrast to the lusterless groundmass. In thin sections the mica appears fibrous and may be detected by its nearly parallel extinction, good relief and strong birefringence. The largest fibers are 0.01 mm. long and only a third as wide.

Most fragments of the shale do not effervesce in cold acids but in thin sections the presence of carbonate minerals is indicated by the high birefringence of many minute grains scattered through the matrix of the rock. From washed cuttings of the shale minute brownish concretions and larger dense fragments were obtained which qualitative tests proved to be siderite containing a small quantity of magnesium. It is likely that the same mineral occurs in the fine grains observable only in thin sections.

Pyrite was observed in washed cuttings of the shale. It occurs in minute concretions and crystals about one millimeter in diameter and as a replacement material in fossils. It constitutes less than one per cent. of the rock. Many samples containing this mineral come from wells located in the hypothetical fault zone suggested by Somers [16] but not all of the samples came from this part of the field. In fact, the distribution of pyrite seems too general to substantiate the conclusions reached by him.

In his study of the cap rock, Somers has attempted to show that the distribution of pressure twinning in calcite, of fractured and recemented calcite, and of secondary pyrite may be used to determine the trend of subsurface faults. If all his evidence is plotted on a single map, however, the location of a zone of faulting capable of explaining the observed phenomena becomes difficult. Moreover, his maps show only the locations of wells in which the phenomena are "relatively abundant," and one may infer that samples from other wells exhibit the same characteristics to some extent.

[16] Somers, R. E., *op. cit.*, p. 319.

The present writer has observed pyrite in the cap rock from more wells than has been indicated by Somers and concludes that pyrite is widely scattered through the cap rock rather than confined to certain zones. Of the 54 samples examined, 49 contain pyrite in the shale, in the cap rock, or in both. Although cap rock samples were examined only casually, pyrite was noted in those from wells designated in Fig. 1 by a cross. The distribution seems too general to be accounted for on the basis of faulting especially in view of the fact that pyrite is a common mineral in sedimentary rocks.

Pressure twinning as a petrographic criterion of faulting should be regarded cautiously. The ease with which twinning may be produced synthetically during the grinding of thin sections is well known and seems sufficient in itself to preclude the use of this phenomenon as a criterion of faulting. Fracturing and recementation of calcite may be due to recrystallization wholly unrelated to faulting[17] and, therefore, this criterion is also to be regarded with some caution.

COLOR.

The possibility of using color as an index of metamorphism was suggested by the Cromwell Project Committee. The changes brought about in the composition of a coal bed subjected to differential metamorphism are well known. White[18] has used a high ratio of fixed to volatile carbon as an index of a degree of metamorphism unfavorable to the presence of oil. Many regions do not contain coal beds but are underlain by carbonaceous shale. If the ratio of the fixed to the volatile carbon in such rock could be determined, its use as an index of metamorphism in regions where coal beds are absent would be valuable. Several attempts[19] to determine the fixed and volatile carbon in carbo-

[17] Grawe, O. R., "Some Breccias of the St. Louis Formation in the St. Louis, Missouri, Region," Washington University Studies, vol. 13, 1925, Scientific Ser. No. 1, pp. 52–58.

[18] White, David, *op. cit.*

[19] Fieldner, A. C., Selvig, W. A., and Taylor, G. B., "The Determination of Combustible Matter in Silicate and Carbonate Rocks," U. S. Bureau of Mines Technical Paper 212, 1919.

White, David, Personal communication in which he states, "The results from

naceous shales have met with only partial success for, although many carbonaceous shales are quite black, they may contain only small amounts of organic matter. When this is as well disseminated through the inorganic matrix as it is in the shale from Cromwell, the determination of fixed and volatile carbon becomes quite difficult. Therefore, the possibility of utilizing color changes in lieu of chemical changes as an index of the metamorphism of carbonaceous shales was investigated.

Several methods of determining the color of carbonaceous shale were devised.[20] Qualitative estimates of color by comparing samples of shale to a standard color chart and to one another were found to be wholly inadequate because of variation in personal opinion. This difficulty was overcome by measuring the color of the shale with an Ives tint-photometer. This is a special type of colorimeter employing monochromatic glass screens for analyzing the color of the light transmitted or reflected by solids and liquids. A numerical expression for each component color is obtained, each value representing the per cent of the monochromatic color in the sample compared to the amount of that color in white light. The standard screens used are the primary colors red, green and blue but two auxilliary colors, yellow and a special peacock blue, are also supplied with the instrument. If the amount of red in the light reflected from a sample is to be determined, the red filter is placed in the field of observation, of which one half is illuminated by light from the unknown sample while the other half is illuminated by white light. Since the red filter permits only red rays to pass through, proper adjustment of a shutter permits a reduction in the intensity of these rays in the white light until it equals that from the sample. The two half fields then merge into one and the intensity of the red beam may be read directly from the position of the shutter control lever. If the scale reading is 24.5, for example, the light from the sample

tests of a number of shales appear very promising, but tests of three of the so-called black shales from the Cromwell field have, on the other hand, been very discouraging."

[20] Grawe, O. R., "Quantitative Determination of Rock Color," *Science*, vol. 66, n. s., 1927, pp. 61–62.

contains 0.245 as much red as is present in the standard white light. This method is free of personal judgment and yields a numerical expression of color which lends itself to graphic presentation.

The application of this method to the color analysis of shale involves some special preparation of the samples. Comparable results are obtained only when each sample presents the same type of reflecting surface to the incident light. Since the shale under investigation occurs in fragments too small to permit direct analysis of the color of the massive rock, the color of the rock powder or streak was determined. A suitable amount of each sample, 10 to 20 grams, was passed through a Braun pulverizer and sieved through a 230-mesh screen. A portion of the powder passing through this screen was mounted on a card large enough to cover the block upon which it was to be placed. Surfaces of similar density and smoothness were insured by evenly distributing each sample upon the card and then compacting it by rolling under a cylindrical two kilogram weight, a piece of glazed cardboard being inserted between the powder and the weight during the rolling process.

Forty-seven samples of the black shale overlying the Cromwell cap rock were analyzed colorimetrically and very similar results were obtained in most cases. The only outstanding exception is the shale from well No. 38, which properly may be omitted from consideration since the sample is known to be inaccurate. To give a complete tabulation of all data would involve needless repetition therefore only a few results taken from wells along C–C of Fig. 1 are recorded in Table I.

Although the color of the shale is apparently black, the color determinations of the streak show that there is a decided reddish brown component. If the shale consists of white inorganic material mixed with a pure black, the streak would be neutral gray, consisting of black diluted with white light, and the ratio of the component colors would be the same as for white light, that is, the Ives tint-photometer readings would be the same regardless of the color screen used. Such is not the case. The

TABLE I.

COLOR ANALYSES OF STREAKS OF BLACK SHALE, TOP OF CAP ROCK, CROMWELL POOL, OKLAHOMA.

Well and Sample No.	Depth of Cap Rock below Sea Level.	Ives Tint-Photometer Readings ± 0.5.					Total Luminosity ± 0.5.	Equivalent Admixture of Black ± 0.5.	Ridgway Color of the Massive Rock.
		Primary Colors.			Accessory Colors.				
		Red.	Green.	Blue.	Mono Yellow.	Mono P-Blue.			
61	2595	28.5	27.5	24.0	27.0	24.0	27.4	72.6	Blackish slate No. 3
55	2569	29.0	27.5	23.5	26.5	22.5	27.4	72.6	
56	2562	25.5	25.0	24.0	26.0	24.0	24.9	75.1	
67	2505	29.0	27.5	24.0	27.5	25.5	27.4	72.6	Slate Color No. 4
65	2475	29.0	28.5	25.0	29.0	26.5	28.2	71.8	Blackish slate No. 3
26	2513	29.0	27.0	25.5	27.5	26.0	27.2	72.8	Slate color No. 4
38	2540	37.0	34.5	32.0	35.0	33.0	34.7	65.3	
31	2553	29.5	27.0	25.0	27.0	26.0	27.3	72.7	Slate color No. 4
30	2560	29.5	27.0	24.0	27.0	26.0	27.2	72.8	Blackish slate No. 3
Highest determination exclusive of sample No. 38		30.0	28.5	27.0	29.5	26.5	28.6	71.4	
Lowest determination exclusive of sample No. 38		25.5	23.5	21.0	24.0	22.0	23.6	76.4	
Weighted mean exclusive of sample No. 38.....		29.0	27.0	24.5	26.5	25.5	27.1	72.9	

green, and particularly the red, components are in slight excess of the blue which indicates that the color is really a reddish brown darkened by the admixture of black. This color is probably due in part to the brown siderite and in part to the organic matter that appears black but really is reddish brown as revealed in very thin sections.

The amount of admixture of black in the color can be calculated from the photometer reading by means of certain luminosity factors. These factors represent the amount of light reflected by each color and are .19, .71 and .10 for red, green, and blue light respectively. When the photometer readings are multiplied by their respective factors the luminosity of the sample due to each color is obtained and their sum is an expression of the total luminosity of the sample. The equivalent admixture of black is the difference between perfect and actual luminosity. Using the results obtained for sample 61 as an example:

	Red.	Green.	Blue.
Scale readings	28.5%	27.5%	24.0%
Luminosity factor	.19	.71	.10
Luminosity	5.415%	19.525%	2.40%
Perfect luminosity			100%
Total luminosity values			27.44%
Equivalent admixture of black			72.56%

The uniformity of the color of the shale throughout the field is indicated by the general agreement of analyses and particularly by the frequency of certain color values. Among the 46 samples, the colors of 33 contain 28 to 29 per cent. red, 36 contain 27 to 28 per cent. green, 32 contain 24 to 25 per cent. blue, 32 contain 27 to 28 per cent. yellow and 39 contain 25.5 to 26.5 per cent. peacock blue.

The forces which produced the Cromwell dome evidently had no differential effect upon the color of the rock involved in the folding. This is illustrated in Fig. 2. Well locations are plotted as abscissæ and structural elevations and color values are plotted as ordinates. From these graphs it is apparent that, if the unique

color of sample No. 38 is omitted because of the known inaccuracy of the sample, the color graphs show little variation from well to well although the structure profile shows a decided minimum between wells No. 30 and No. 31 and a decided maximum in the vicinity of well No. 65.

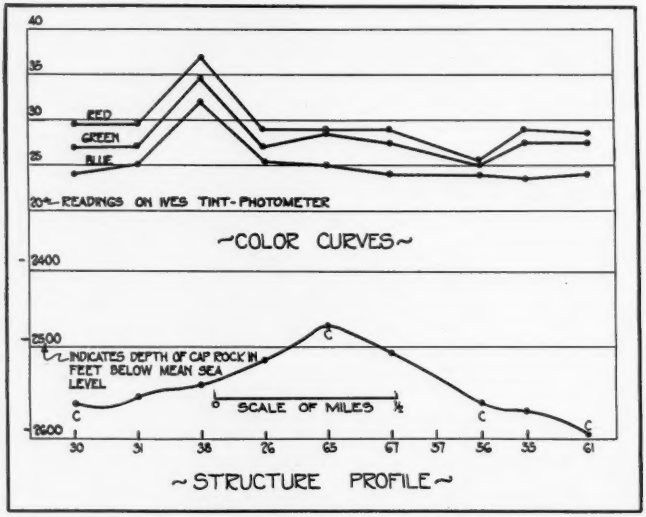

FIG. 2. Comparison of the color with the structure of the shale overlying the Cromwell cap rock along the broken line C–C, Fig. 1.

SPECIFIC GRAVITY.

If local forces of the type suggested by Gardner [21] caused the doming in the Cromwell Pool, a variation in the degree of compaction of the shale overlying the cap rock would be expected. The density of the shale should be higher on the crest than on the flanks of the fold. A determination of the specific gravities of 33 samples shows that this is not the case.

A new Jolly balance was used, the shale being sufficiently impervious to water to permit the direct use of this instrument.

[21] Gardner, J. H., *op. cit.*, p. 239.

Readings on submerged samples did not change during a five minute interval and duplicate determinations checked well within one per cent. when care was used to select fragments free of visible pyrite and calcareous concretions. Table II. indicates the frequency of the results obtained.

TABLE II.

SPECIFIC GRAVITY OF SHALE, TOP OF CAP ROCK, CROMWELL POOL, OKLAHOMA.

Sp. Gr.	No. of Samples.	Sp. Gr.	No. of Samples.
2.61	1	2.67	1
2.63	12	2.68	1
2.64	9	2.69	1
2.65	4	2.71	1
2.66	2	2.88	1

The exceptionally high value, 2.88, obtained for the sample from well No. 13 may be due to secondary pyrite which is known to occur in shale from this well. The other 32 values agree fairly well, 27 being within one per cent. of the weighted mean, 2.64. Such results show that local metamorphism would not result from the forces that produced the doming. The slightly abnormal specific gravities of the samples from wells Nos. 5, 12, 13, 25, 29 and 49 are without structural significance since they have dissimilar structural positions.

In order to prove that the method used is capable of detecting significant variations in specific gravity, the writer determined the specific gravities of a series of samples taken from other stratigraphic horizons. Although the accuracy of sampling and of measuring depths do not approach that for the shale overlying the cap rock, the method is sufficiently accurate to show that there is a general increase in specific gravity of the shale with stratigraphic depth. The determinations recorded in Table III. and presented graphically in Fig. 3 represent an aggregate of data from several wells. No large number of samples were available from any single well or from any single horizon. These results are particularly interesting since they illustrate compaction in a

section containing 82 per cent. of shale,[22] which according to Leith and Mead,[23] is the amount of shale present in an average section of sedimentary rock.

TABLE III.

SPECIFIC GRAVITIES OF SHALES IN THE CROMWELL OIL FIELD.

Well Number.	Elevation of Shale above Top of Cap Rock.	Sp. Gr.	Well Number.	Elevation of Shale above Top of Cap Rock.	Sp. Gr.
64	2789	2.42	5	1095	2.53
4	2535	2.41	5	1010	2.54
3	2382	2.50	3	1025	2.56
3	2215	2.49	3	865	2.56
3	2165	2.50	5	845	2.58
35	2138	2.48	5	820	2.54
3	2025	2.43	26	697	2.57
3	1955	2.50	53	634	2.56
3	1915	2.49	3	630	2.62
3	1825	2.50	32	470	2.58
64	1820	2.50	3	465	2.58
4	1810	2.51	12	445	2.59
65	1682	2.57	65	394	2.59
3	1675	2.52	15	187	2.58
35	1587	2.52	27	181	2.61
3	1584	2.50	32	174	2.58
3	1420	2.52	65	172	2.60
65	1399	2.54	26	164	2.58
3	1260	2.52	50	149	2.56
64	1160	2.56	3	142	2.58
56	1139	2.56	63	141	2.57
3	1115	2.57	Average	0	2.64

The increase in specific gravity from 2.42 at a distance of 2800 feet above the top of the cap rock to 2.64 at the top of the cap rock is equivalent to a porosity reduction of about six per cent. This increase with depth is represented in a very general way by the curve in Fig. 3 and it is likely that a detailed study of the specific gravity of the shale at many horizons would show some breaks in the curve. For example, the points to the left of the curve near the base indicate that the average specific gravity

[22] Levorsen, A. I., "Geology in Seminole County," Oklahoma Geological Survey, Bull. 40–BB, 1928, p. 16.

[23] Leith, C. K., and Mead, W. J., "Metamorphic Geology," 1915, p. 63.

of the shale 150 feet above the cap rock is about 2.58. If a larger number of determinations should prove this to be correct, the curve would show a sharp break near the base, for the average specific gravity of 2.64 for the shale immediately on top of the cap rock is substantiated by 27 out of 33 determinations. Such a

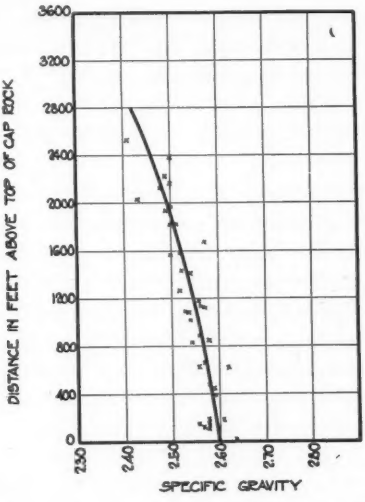

FIG. 3. Compaction of shale, Cromwell Pool, Oklahoma.

break would be in agreement with certain other evidence of one or more unconformities in this part of the section and it is likely that others would be detected in the upper part of the section if a sufficiently large number of samples were available.

CHEMICAL COMPOSITION.

Hygroscopic Moisture.—Sixteen gram-samples of shale powdered to pass a 230 mesh screen were dried in duplicate to constant weight at 105° to 110° C. The loss varied from 1.88 to 2.30 per cent. but eleven samples checked the average, 2.06 per cent., within the limit of error, (0.12). This may be considered good

agreement in view of the difficulty in drying powdered shale to constant weight.

Extraction Products.—Two samples of shale pulverized to pass a 230 mesh sieve, were extracted with benzene by refluxing the solvent for one hour in a Soxhlet extractor. After evaporation on tared watch glasses, the extracts left a brown residue much like bees' wax in odor, viscosity and appearance, the yield in the two cases amounting to 0.024 and 0.017 per cent. respectively. Similar results were obtained with acetone, alcohol, ether, and carbon tetrachloride and the small yield did not make further determinations seem feasible in view of the size of samples available.

Distillation Products.—A 200 gram sample of partially pulverized shale was heated for several hours in a Pyrex distilling flask, the temperature being kept near the softening point of the glass. The vapors were passed through a condenser and through an absorption chamber containing standardized hydrochloric acid, qualitative tests having indicated an evolution of ammonia. The products of destructive distillation were water, ammonia and a tarry odor but no bituminous or oily material was obtained. The quantity of ammonia distilled was equivalent to a nitrogen content of 0.10 per cent., which is in agreement with the results of dry distillation of other shales carried on by Winchester.[24] Although it is probable that not all the nitrogen was driven off as ammonia, the carbon-nitrogen ratio for this shale is at least 7: 1, a value markedly different from that for coal, more nearly 50: 1. This indicates that the organic matter in the shale is quite different from that in coal. In view of the results obtained by other tests, a detailed study of the variation in nitrogen content of the shale did not seem practical.

Carbon and Carbonate.—Because of the difficulties and time involved in determining the carbon and carbonate content of the shale, only nine samples were analyzed. These came from wells located along the broken line C–C of Fig. 1. The samples were pulverized to pass a 230 mesh screen and were analyzed in dupli-

[24] Winchester, D. E., "Results of Dry Distillation of Miscellaneous Shale Samples," U. S. Geol. Survey Bull. 691, 1919, pp. 51–55.

cate by A. H. Kunz and J. A. Reddick working under the supervision of Dr. Stephen Popoff.[25]

The analytical procedure employed was that used in steel analysis. A weighed sample was burned in a combustion furnace in an atmosphere of dry oxygen free of carbon dioxide. The gaseous products of combustion were led over hot lead peroxide to insure complete oxidation and were then passed through two absorption chambers, one filled with dehyrite and the other with ascarite. The increase in weight of the former was taken as a measure of the water of combustion, which included 2.06 per cent. of hygroscopic moisture and the water of hydration in such minerals as sericite and kaolinite. The increase in weight of the ascarite was indicative of the amount of carbon dioxide liberated. This gas was produced from two sources, combustion of organic carbon and decomposition of carbonates. The amount of carbon dioxide derived from carbonates was determined by another analysis. A weighed sample of powdered shale was heated with dilute hydrochloric acid in a flask provided with a reflux condenser. The carbon dioxide liberated was sucked through a solution of silver sulphate in sulphuric acid to remove any hydrogen sulphide that might have been produced by the action of the acid on the pyrite and then through dehydrite and ascarite by which it was absorbed. The increase in weight of the ascarite determined the amount of carbon dioxide set free. The difference between the total carbon dioxide liberated on combustion and that liberated by the acid treatment was taken as a measure of the organic content of the shale.

The results of the analyses (Table IV) are in agreement with petrographic observation. The organic carbon content of the rock averages 0.68 per cent. which is in agreement with the one per cent. of organic matter estimated from thin sections. The amount of carbonate necessary to account for an average carbon dioxide content of 1.41 per cent. is higher than would be estimated from petrographic analysis. If nearly all this carbon

[25] Funds for this work were supplied by the Graduate College of the State University of Iowa and the work was done in the Department of Chemistry of that institution.

TABLE IV.

CARBON CONTENT OF BLACK SHALE OVERLYING CROMWELL CAP ROCK.

Well No.	Depth in Feet below Mean Sea Level.	Per Cent. Carbon Dioxide Produced by Combustion.			Per Cent. of Organic Carbon ± 0.02.	Per Cent. of Water Produced by Combustion ± 0.3.
		Total ± 0.1.	From Carbonates ± 0.05.	From Organic Matter ± 0.1.		
61	2595	3.96	1.42	2.54	0.69	6.97
55	2569	4.66	1.58	3.08	.84	5.88
56	2562	3.49	.92	2.57	.70	7.43
67	2505	3.88	1.32	2.56	.70	7.31
65	2475	3.64	1.50	2.14	.58	7.23
26	2513	3.65	1.40	2.25	.61	7.58
38	2540	5.21	2.09	3.12	.85	6.76
31	2553	3.70	1.30	2.40	.65	7.26
30	2560	4.34	1.83	2.51	.68	7.94
Average, exclusive of No. 38.....		3.91	1.41	2.51	.68	7.20

dioxide is combined with iron, as qualitative tests indicate, the average siderite content is approximately 3.5 per cent. Since no sample gave off enough hydrogen sulphide during the acid treatment to appreciably darken the silver sulphate solution, the average pyrite content of the shale must be exceedingly low. This may account for the fact that no pyrite was observed in thin sections although local concentrations in the form of minute crystals, concretions and pyritized fossils were observed during a binocular examination of washed cuttings.

The lack of any relationship between the composition and the structure of the shale is apparent. With the exception of the samples from wells No. 55 and No. 38, there is no variation among analyses but what could be accounted for on the basis of slight differences in sedimentation. Certainly, local deformation cannot be used as an explanation. The sample from well No. 38 is known to be inaccurate but its analysis is included to show how much such a sample does differ from analyses of samples which were well taken. The variations shown from well to well, as indicated by the other analyses, do not occur at significant points

on the structure. Fig. 4 shows that the composition graphs have maxima or minima at wells No. 38 and No. 55 while the structure profile has a maximum at well No. 65 and a minimum between wells No. 30 and No. 31. This points to the conclusion that the forces which produced the doming in the Cromwell field did not produce local metamorphism and that they were probably regional in character.

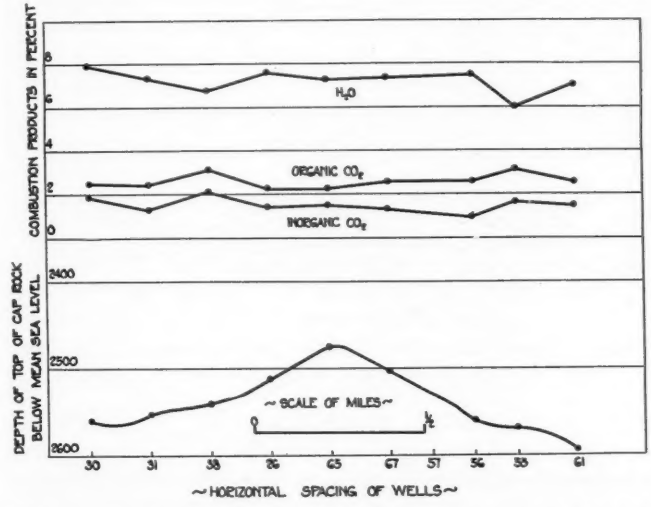

FIG. 4. Comparison of the composition with the structure of the shale overlying the Cromwell cap rock along the line C–C, Fig. 1.

From two independent investigations of the black shale overlying the cap rock of the Cromwell sand the same conclusion has been drawn. Both lithologic and chemical analyses show that the present character of the shale is independent of the structure. One might ask, "Do the lithologic properties and chemical composition of the rock show any agreement among themselves?" This question may be answered by pointing out the influence of the constituents of the shale upon its color. One would expect the color to be controlled largely by the amount of organic matter

present, but, since the organic matter is not as abundant as the brown siderite, the color is more dependent upon the latter than upon the former. The color graphs of Fig. 5 more closely paral-

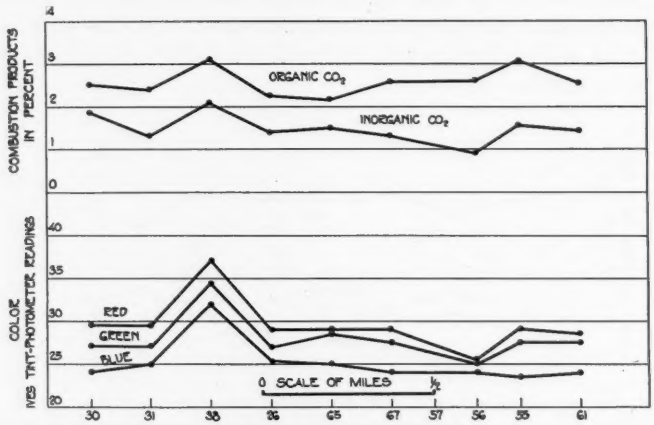

FIG. 5. Comparison of the color with the composition of the shale overlying the Cromwell cap rock along the line C–C, Fig. 1.

lel the inorganic carbon dioxide graph than they parallel the organic carbon dioxide graph. Both siderite and organic matter add a brown component to the color but the former also lightens the color by the addition of white whereas the latter tends to darken the color by the addition of black. The net effect of these two components produces the actual color of the shale.

SUMMARY AND CONCLUSIONS.

An investigation of 54 samples of the black shale overlying the cap rock of the Cromwell sand in the southern part of the Cromwell oil field of Oklahoma has shown that the lithologic properties and the composition of the shale are as constant as can be expected of any rock. Everywhere the shale has much the same characteristics and no variations occur which can be correlated with local metamorphism produced by structure-forming

forces. Slight differences in color have been detected but they are independent of the structure. They seem to accompany changes in composition, especially changes in carbonate content and such changes may best be explained on the basis of sedimentation rather than on the basis of metamorphism accompanying deformation. Although the shales from different stratigraphic horizons show an increase in specific gravity with depth, the specific gravity of the shale from a single horizon is constant, regardless of the structure. Gardner's [26] suggestion that a careful study of the properties and composition of the shale in the low dome-like structures of the Mid-Continent field "may prove the presence of slight localized metamorphism" has not been substantiated and it is unlikely that local forces of the type postulated by Gardner could have produced the Cromwell dome.

In conclusion the writer wishes to express his regret that samples of wider distribution were not available. He also wishes to express his appreciation of the aid given to him by those interested in the project. He is particularly indebted to J. H. Gardner, who initiated and financed the investigation, to K. C. Heald, Chairman of the Cromwell Project Committee, and to A. C. Trowbridge of the State University of Iowa.

[26] Gardner, J. H., *op. cit.*, p. 239.

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A MOTHER LODE GOLD ORE.

CARLTON D. HULIN.

In connection with one of the first cases arising from the enforcement of the so-called California "High Grade Law," passed in 1925, the writer came into possession of a group of specimens of gold ore from the Kennedy Mine which are of sufficient interest to warrant a brief description. The Kennedy, one of the largest of the gold mines operating on the Mother Lode, is located not far from Jackson, in Amador County, California. It is one of the older mines of the region, having been first located in 1856. The workings of the mine have reached a depth of 4,764 feet.

The several specimens which furnish the subject matter of this paper were obtained from stopes on the 3,900 foot level which were being mined during the last several months of 1925. The chief interest in this group of specimens centers in the fact that the principal gangue represented consists of the mineral apatite. In so far as the writer has been able to ascertain, the occurrence of apatite as a vein mineral has not been previously reported from any of the gold deposits of the Sierra Nevada of California.

The Apatite.—The apatite-bearing vein matter occurred cutting the deposit in the form of a definite veinlet which was from one to two inches in thickness. The field relations are only imperfectly known but apparently the apatite veinlet cut earlier-deposited quartz. Portions of the veinlets have well defined walls which locally show evidence of movement. A rude banding is also manifest, resulting in part from thin plates of slaty wall rock being incorporated in the veinlet and so oriented that their long axes lay in the plane of the veinlet, and in part from bands of sulphides which were introduced along planes of shearing which cut and followed the veinlet.

The apatite is pale grayish-white in color and on account of its well developed cleavages it possesses the casual appearance of the

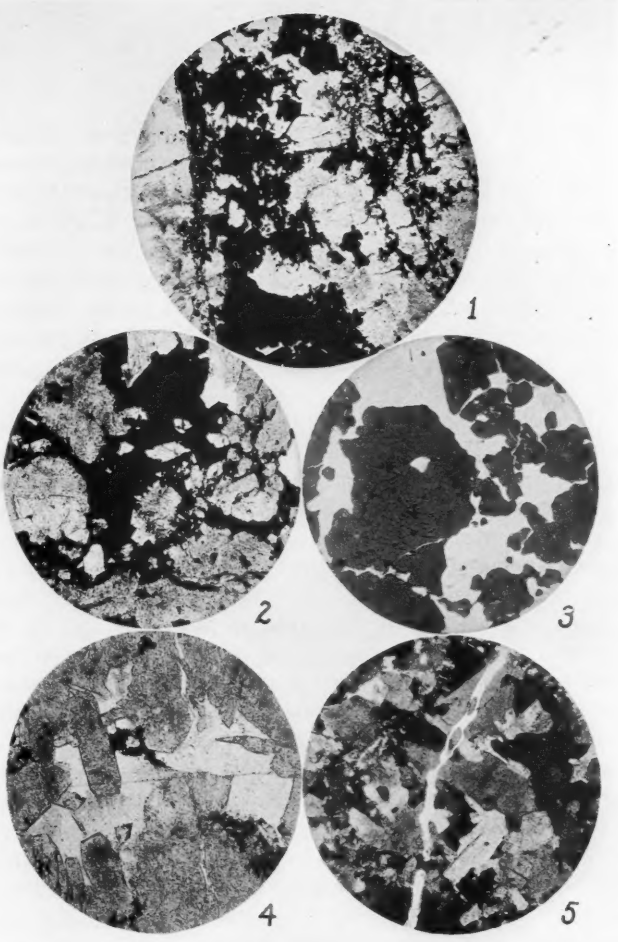

FIG. 1. Brecciated and shattered apatite (light) penetrated and replaced by sulphides and gold (black). Thin section, ordinary light, × 6.

FIG. 2. Apatite (mottled white) penetrated and replaced, first by quartz (white), and after further brecciation by sulphides and gold (black). Thin section, ordinary light, × 24.

FIG. 3. Apatite (gray) penetrated and replaced by gold (white). A rounded area of chalcopyrite (light gray) appears in the gold near the top of the section. Pol. surface, × 60.

FIG. 4. Apatite (gray) intercrystallized with quartz (white). The sulphides (black) were introduced along later fractures as was the thin veinlet of quartz extending vertically through the section. Thin section, ordinary light, × 26.

FIG. 5. Granular aggregate of interlocking apatite crystals cut by quartz veinlet. Thin section, crossed nicols, × 25.

albite which is not uncommon in the Mother Lode ores. It seems quite probable that apatite in ores of the Mother Lode may on occasion have been mistaken for albite. The identification of the apatite was first made by the use of optical methods, the mineral possessing all the normal optical properties for apatite. Qualitative chemical tests were later made for lime, phosphate, fluorine and chlorine. Strong reactions were obtained for the first three tests, but the test for chlorine was essentially negative. The apatite therefore must be classed as the common fluorine-bearing variety, fluor-apatite.

The apatite, which in thin section occurs as interlocking granular aggregates, is somewhat cloudy, shows a rather good development of both the basal and prismatic cleavages, and tends to have a prismatic habit. There is a slight tendency for the prismatic growth to be roughly normal to the walls of the veinlet. Effects of brecciation and granulation have to some degree masked this tendency. The more finely brecciated apatite commonly shows a range of grain size of from 0.01 to 0.05 mm., and the unbrecciated grains range from less than 0.1 to 2. or 3. mm. in mean diameter. A fair average for the unbrecciated grains would be 0.75 mm. long by 0.30 mm. in diameter (Fig. 5), the individual crystal grains usually having lengths of from two and a half to three times their diameter, though occasional grains possess a ratio of elongation as great as six. The brecciated apatite may be cemented by later apatite or by any of the later minerals.

The apatite occurs associated in the ore with quartz, strengite ($FePO_4 \cdot 2H_2O$), pyrite, sphalerite, carbonates, sericite, galena, chalcopyrite and native gold, the apatite commonly composing about 75 per cent. of the specimen.

The rather well developed basal and prismatic cleavages of the apatite, together with its general low strength factor, have rendered it extremely susceptible to stress action during the mineralization; in consequence the occurrence of innumerable veinlets and stringers of quartz, sulphides and gold penetrating the apatite along fractures and cleavages is both noteworthy and characteristic (see figures). Although the positions occupied by the later minerals were controlled by the presence of open fractures and

cleavages, more or less replacement of the apatite accompanied the filling of these open spaces.

THE MINERAL RELATIONSHIPS.

On account of repeated shattering and brecciation during the mineralization, the periods of introduction of the various minerals present can be fixed with considerable accuracy (Fig. 6).

Apatite and Quartz.—The occurrence of quartz older than the apatite is attested by the presence of occasional angular fragments of quartz included in the apatite. Some of these angular quartz fragments are incorporated within individual crystals of apatite. Quartz deposited simultaneously with the apatite is shown by intercrystallized areas of the two minerals (Fig. 4). In such cases the apatite is automorphic with respect to the quartz, due to its stronger power of crystallization. Late quartz is shown by quartz-filled fractures cutting the apatite, and by minor quantities of quartz deposited with the sulphides at least as late as the time of introduction of some of the galena. In such cases the quartz may form a selvage between the sulphide and apatite, may penetrate the sulphides, or may be intergrown with them.

All the sulphides, the carbonates, the sericite and the gold are distinctly later than the latest apatite; each of these cut and penetrate the apatite or include angular apatite fragments.

Strengite.—Locally intergrown with the apatite are a few minute prisms of a red mineral which possesses the optical properties of the iron phosphate, strengite. The largest of these prisms is only 0.5 mm. in length and 0.02 mm. in diameter. The mineral shows parallel extinction, is faintly pleochroic in shades of deep pink or red ($Z' > X'$) and possesses a positive elongation. The refractive index is noticeably above that of the enclosing apatite, and the birefringence is moderately high.

The formation of strengite might well be expected during the time of deposition of the latest of the apatite and of the earliest of the pyrite, since only at this time were both iron and phosphate present together in the mineralizing solutions.

Pyrite.—The pyrite appears to be entirely later than the apatite, replacing it in large euhedral grains which on their borders com-

monly become irregular in detail and show projecting tongues which penetrate the apatite along cleavages and fractures. Considerable pyrite also occurs as irregular patches filling fractures which cut the apatite. The pyrite is usually associated with a little quartz and may in turn be cut by narrow quartz seams which themselves contain pyrite. Although some of the pyrite is late, the bulk of the pyrite is cut and penetrated by all the other sulphides and by gold.

Carbonates.—Carbonates, either calcite or ankerite, are present in minor amount and are entirely later than the apatite. Carbonate veinlets cut quartz veinlets, which in turn fill fractures that cut the mass of the apatite. Some carbonates were observed to fill fractures that cut across pyrite, and galena was observed to fill fractures and to follow cleavages in the carbonates. The bulk of the carbonates are roughly contemporaneous with the sphalerite; in many cases the two minerals are intercrystallized.

Sericite.—Sericite in thin platy aggregates is present in minor amount and is roughly contemporaneous with the carbonates and sphalerite. Where present it is almost invariably directly associated with the carbonates, and commonly lies along the boundary between carbonate and sphalerite or carbonate and galena. In one case galena and sericite were observed together in a fracture that cuts apatite. No sericite was observed which is not definitely at least as young as the sphalerite or carbonates.

Sphalerite.—Sphalerite is present in moderate amount though decidedly subordinate in quantity to the pyrite, galena and chalcopyrite. It is later than most of the pyrite, since it commonly fills fractures that cut that mineral. The sphalerite in turn is earlier than the bulk of the galena and chalcopyrite, as it is cut and replaced by these minerals throughout most of the sections examined. Apparently sphalerite may be easily replaced by either galena or chalcopyrite.

Galena.—Of the sulphides, galena is second in abundance only to the pyrite. The earliest of the galena is definitely later than most of the sphalerite and in consequence the galena commonly cuts and replaces the other minerals, excepting only the gold and chalcopyrite. Although largely later than the sphalerite, the time

overlap between the sphalerite and galena is demonstrated by the occasional occurrence of the two minerals together in narrow veinlets that cut the apatite.

Chalcopyrite.—The galena and chalcopyrite appear to be quite closely related in time, though the prevailing evidence offered by crosscutting relationships suggests that although largely contemporaneous, the chalcopyrite commonly outlasted the galena. The chalcopyrite is present in moderate abundance, being subordinate in amount to the pyrite and galena, but somewhat more abundant than the sphalerite. Although the bulk of the chalcopyrite is manifestly roughly contemporaneous with the galena, a certain amount of it occurs as minute globules or blebs disseminated through practically all the sphalerite. The average diameter of these blebs of chalcopyrite approximates 0.0035 mm., the range in size being from about 0.01 mm. to less than 0.0003 mm.

The chalcopyrite, though distinctly later than the pyrite, is so commonly directly associated with that mineral as to suggest that the chalcopyrite resulted in part from interaction between copper-bearing solutions with pre-existing pyrite rather than by direct deposition from solutions carrying copper, iron, and sulphur.

Gold.—Gold was definitely the last mineral to be deposited, overlapping in time of deposition only with galena and chalcopyrite. The overlap in each case, however, was only partial. In one section a band of galena, unaccompanied by gold, was ruptured by a cross-fracture which was later filled by a veinlet of quartz. Still later shearing formed new openings along the band of galena. These were filled with gold, and where the breaks passed through the quartz-filled cross-fracture, only gold was deposited. The close time relationship between gold, galena and chalcopyrite results in these minerals characteristically possessing a similar spacial distribution in the ore. The time relation between the gold and chalcopyrite being closer than that between the gold and galena, the gold occasionally occurs in areas not directly associated with galena, whereas appreciable areas of gold are rarely without one or more rounded blebs of chalcopyrite. Veinlets of gold that cut the apatite along cleavages or fractures and

are free from other minerals, characteristically show an occasional such bleb of chalcopyrite.

Although the closest time relation existed between the gold and the galena and chalcopyrite, the gold in these specimens repeatedly cuts and penetrates the other minerals along cleavages or fractures. Thus the apatite and carbonates contain numerous thin veinlets of gold that fill narrow openings. These, in large part,

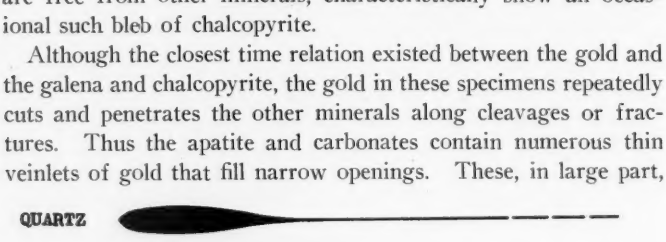

FIG. 6. Sequence of introduction of minerals.

were controlled by the cleavages of the respective minerals, but in part, at least, represent random fractures. Similar veinlets of gold fill fractures that cut pyrite and sphalerite, but they are much less common in these minerals than in any of the other abundant minerals of the ore, excepting only the quartz. Gold-filled fractures are not uncommon, however, even in the quartz. The gold in the fractures that cut any of the previously mentioned minerals, may spread out, and replace the mineral that adjoins the original fracture and thus largely destroy the evidence of the original fracture control of the distribution of the gold.

The conclusion appears justified that the association of gold with other minerals in an ore is strictly dependent upon two factors, these being (1) the relation in time of deposition of the several minerals as compared to the gold, and (2) the ease of fracturing of the potential mineral associate. The ease of fracturing is manifestly dependent upon the strength or toughness of the mineral and upon the presence or absence of cleavage. To some extent the relative ease of replacement of the several minerals by gold may be a factor—a factor, however, that is decidedly subordinate to the other two.

Thus, in these particular specimens, although the chalcopyrite is most closely related to the gold in time, the galena is an almost equally common associate of the gold, the slightly less favorable time of deposition being offset by the lower strength factor and perfect cleavage possessed by the galena, which render it easily fractured and hence open to the gold-depositing solutions. The apatite is a common host for gold in spite of its much earlier time of deposition, due strictly to its well developed cleavages and general low strength factor. The carbonates appear equally favorable, whereas pyrite and sphalerite are much less commonly associated directly with the gold. Quartz is the least favorable of all the minerals present, due to its lack of cleavage and to its relative toughness as compared with the weaker and more brittle sulphides. Arsenopyrite, although not present in the specimens studied, would be more favorable than pyrite or sphalerite, but less favorable than galena or chalcopyrite.

In summary, the relative degree of favorability of the several host minerals for gold as observed in these ores is (1) chalcopyrite, galena, apatite, carbonates; (2) pyrite, sphalerite; and (3) quartz.

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GRAPHIC INTERGROWTH OF NICCOLITE AND CHALCOPYRITE, WORTHINGTON MINE, SUDBURY.

CARL LAUSEN.

DURING the summer of 1929 the writer spent several months examining mines at Sudbury and in the surrounding territory. Among the various samples collected were specimens of niccolite and gersdorffite from the Worthington mine, in the southwestern part of the Sudbury district. Polished surfaces of these gersdorffite-niccolite ores showed an interesting intergrowth of niccolite and chalcopyrite. This intergrowth, sometimes described as a " graphic " texture, is also referred to by some as " eutectic." So far as the writer is aware a graphic intergrowth of niccolite and chalcopyrite has not been described previously, and presents some interesting features in connection with the origin of such textures. Evidence observed in these polished surfaces leads the writer to believe that in this case at least, the intergrowth is due to replacement rather than an unmixing.

GENERAL GEOLOGY.

The general geology of the Sudbury region is, or should be, familiar to all economic geologists; and only a brief description will be given here.

At Sudbury the oldest known rocks are a part of a volcanic complex usually referred to as the Keewatin greenstones. Although the Keewatin in some parts of Ontario contains members that were derived from acid volcanic rocks, the greenstones at Sudbury appear to have been derived essentially from pre-existing igneous rocks which were basic or moderately basic in composition. The original rocks, however, have been so altered, sheared, and recrystallized by metamorphic agencies that little evidence remains of original textures. Associated with, and an

integral part of the greenstone complex, are green schists that originally may have been beds of volcanic ash.

Younger than, and apparently resting unconformably on the Keewatin greenstones is the Sudbury series. This series comprises such rock types as conglomerate, graywacke, quartzite, and slate. Originally these rocks were considered a part of the lower Huronian, but Coleman [1] has clearly demonstrated that they are a separate series and definitely older than the Huronian. These rocks have been intensely deformed and in some cases recrystallized to schists.

Fringing the Sudbury series on the southeast are the quartzites of the Huronian. The prevailing rock is the Mississagi quartzite. In the remapping of the Huronian sediments from Sudbury southwestward, Collins [2] includes the quartzites at the Worthington mine with the Mississagi formation, which is one of the lowest members of the Huronion. These quartzites have also been intensely deformed, and near the Worthington mine dip at steep angles.

Enclosed within a rim of low hills eroded from the micropegmatite is a relatively flat country known as the Sudbury Basin. The basin is underlain by a series of sedimentary rocks named the Whitewater series and is believed to be upper Huronian or Animikie in age.

Although intrusive igneous rocks originally may have formed a part of the Keewatin greenstone complex, the evidence of their intrusive character has been obliterated by metamorphism. The oldest known intrusive rocks in the region are the granite gneisses so common along the north rim of the norite. Such granite gneisses are younger than the Sudbury series and older than the Huronian formation. Along the south rim Coleman recognizes two ages of granite; one, as at the Creighton mine, is older than the norite, and the intrusion near the Murray mine is younger. In the vicinity of Sudbury are intrusions of gabbro and diabase.

[1] Coleman, A. P., "The Pre-Cambrian Rocks North of Lake Huron," Ont. Bureau of Mines, Ann. Rept., vol. 23, pt. 1, p. 35, 1914.

[2] Collins, W. H., Can. Geol. Survey, Lake Huron Sheet, Map 155–A, 2d edition, 1929.

The most important igneous rock of the district is the great laccolithic sheet of norite-micropegmatite with which many of the ore bodies are so intimately associated. The latest intrusive rocks are dikes of diabase. These dikes cut the ore bodies, as well as the younger granite. They are referred to the Keweenawan.

ORE DEPOSITS.

Coleman [3] subdivides the ore bodies at Sudbury into two classes: those which occur at the basic edge of the norite he refers to as "marginal" deposits, and those along dikes or within the footwall of the norite he classes as the "offset" deposits. The Worthington mine belongs to the latter group.

In the general vicinity of the Worthington mine a dike of norite,[4] which Coleman considers an offshoot of the main norite intrusion, cuts the greenstone complex; the Sudbury series; and, at the Worthington mine, the Mississagi quartzite. The general trend of the dike is about N. 45° E. It does not connect with the norite at the present surface but comes to within less than 1.5 miles of the contact.

Along this dike are an interesting group of mines; interesting, chiefly, because of the unusual assemblage of minerals found in the ores. One prospect has been named the Gersdorffite mine because of the presence of this mineral in the ores. Other minerals occurring along this offset are marcasite and niccolite. Not far to the northeast is the Vermillion mine, the original locality for sperrylite. Polydymite and millerite are also reported from this mine.

The ore bodies at the Worthington mine were relatively small compared with the more famous mines of the district such as the Creighton, Frood, and Levack; but the grade of the ore was also comparatively high.[5] Like other ore bodies in the region the massive sulphides consisted essentially of pyrrhotite, pentlandite, and chalcopyrite. An interesting development is the occurrence

[3] Coleman, A. P., "The Nickel Industry," Canada Dept. of Mines, Pub. No. 170, p. 34, 1913.

[4] This rock has been classified as a quartz diorite by Wandke and Hoffman; see ECON. GEOL., vol. 19, p. 195, 1924.

[5] Coleman, A. P., "The Nickel Industry," p. 47, 1913.

of nodules of pyrite enclosing pentlandite. These have been figured and described by Prof. Walker.[6]

Niccolite has been previously described from this mine. Specimens of this mineral were obtained by the writer from several individuals in Sudbury. A few small fragments were also obtained from the dumps at the Worthington Mine. Associated with the niccolite in the same specimen is gersdorffite and the rare nickel arsenide, maucherite. So far as the writer knows this mineral has not previously been described from the Sudbury district. Fortunately, the specimens contained large enough grains of this mineral so that pure material could be dug out of a polished surface with a needle. Not enough material, however, was available for a chemical analysis; and the determination is based on such physical properties as color, hardness, and brittleness. Dimethyl glyoxime indicated abundant nickel, and supplementary blowpipe tests showed the presence of arsenic Other tests also indicate cobalt, copper, and sulphur to be absent. Microchemical tests on polished surfaces also suggest that this mineral is maucherite.

This mineral is of a grayish color with a reddish tinge on a tarnished surface, and in polished sections it is silver white with a pinkish tinge. It is quite brittle and gives a gray streak. The hardness is 5 in Moh's scale; equal to niccolite. As a matter of fact the hardness is so nearly the same as that of niccolite it was found impossible to get enough relief to show on photographing. The boundary between the two minerals was, therefore, shown dotted in the photomicrograph, Fig. 1, accompanying this paper.

A study of polished surfaces suggests that gersdorffite accompanied by vitreous, transparent quartz was deposited first. These minerals were shattered and maucherite introduced, followed closely by niccolite. There has been some replacement of the gersdorffite. The relations are shown in Fig. 1. Chalcopyrite was then deposited and replaced, the niccolite producing a graphic intergrowth as shown in Fig. 2.

Unfortunately, the Worthington mine is now caved and filled

[6] Walker, T. R., "-Certain Mineral Occurrences in the Worthington Mine, Sudbury, Ontario, and Their Significance," ECON. GEOL., vol. 10, p. 540, 1915.

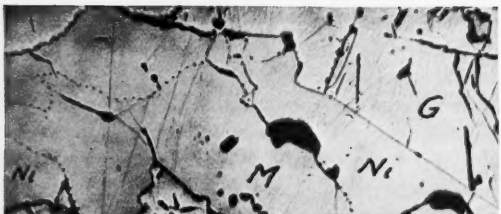

Fig. 1

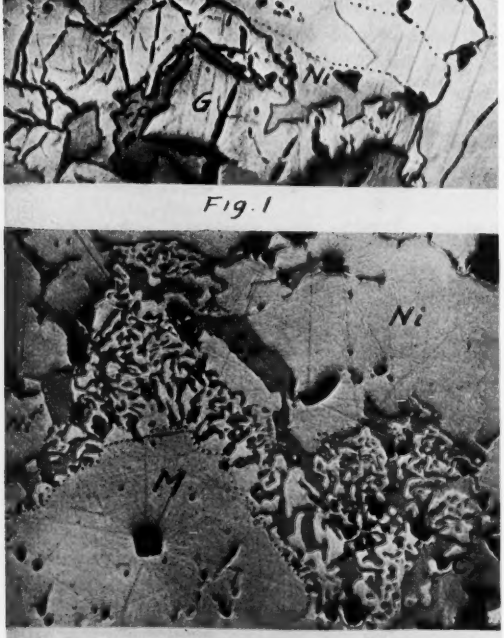

Fig. 2

FIG. 1. Photomicrograph of maucherite-niccolite vein cutting gersdorffite. *G*, gersdorffite, *Ni*, niccolite, *M*, maucherite, *Cp*, chalcopyrite. ×110.

FIG. 2. Photomicrograph of graphic intergrowth of niccolite and chalcopyrite surrounding a grain of maucherite. *Ni*, niccolite, *M*, maucherite, *Cp*, chalcopyrite. ×125.

with water, and it was impossible to observe the relations of these niccolite veins underground. Reliable information obtained from operators indicates that the niccolite veins cut the massive sulphides—pyrrhotite, pentlandite, chalcopyrite,—and had clean-cut walls. Polished surfaces in places, show particles of pyrrhotite and pentlandite, corroded and embayed. They probably represent particles detached from the walls of massive sulphides.

Veins of sphalerite and galena also occur at this mine. A specimen in the possession of Mr. O'Connor, proprietor of the Balmoral Hotel, at Sudbury, shows a veinlet of sphalerite about four inches wide, the central portion of which is filled with galena. Each edge of the vein contained some massive sulphide, such as pyrrhotite, frozen to the sphalerite. In other specimens observed at the Worthington mine the central portion of the sphalerite vein is filled with a comb structure of well terminated, quartz crystals. A resident at the mine informed the writer that the sphalerite veins cut the niccolite veins. Unfortunately, the specimen showing these relations could not be found, and the statement must be taken for what it is worth. A careful study of polished surfaces of niccolite ores fails to show a trace of either sphalerite or galena, and the man may be correct in his observations.

ORIGIN OF THE GRAPHIC TEXTURE.

Considerable diversity of opinion has arisen within the last few years regarding the origin and significance of these intergrowths. The name appears to have originated from the resemblance of these mixed sulphides to intergrowths of quartz and feldspar in graphic granite; and, for some of the textures observed in ores, the term is quite appropriate. When Laney [7] first recognized and described these textures he believed they represented contemporaneous deposition of the two minerals. The observations of Laney led some writers to conclude that the chalcocite in such intergrowths must be hypogene; and the problem, therefore, had an important bearing on the continuation of such richer ores with

[7] Laney, F. B., "The Relation of Bornite and Chalcocite in the Copper Ores of the Virgilina District of North Carolina and Virginia, ECON. GEOL., vol. 6, p. 406, 1911.

depth in certain mines. Ransome [8] suggests, however, that similar intergrowths might well be produced by secondary processes. The writer has observed similar textures in the enriched ores of the Old Dominion mine where there was no doubt regarding the supergene origin of the chalcocite. Rogers [9] observed such textures in the ores of Butte and suggests the chalcocite is an irregular replacement of bornite.

Within the past ten years there has been more and more of a tendency to ascribe the origin of these textures to unmixing. The proponents of this idea, reasoning by analogy with somewhat similar textures in alloys and in some igneous rocks (micropegmatite), hold that at the time of formation the two sulphides were combined, perhaps in solid solution. Changes in physical conditions since the time of formation, chiefly a lowering of temperature but perhaps also other factors, would bring about a segregation of the components of the solid solution by unmixing and diffusion. Schneiderhöhn has been the leading advocate in Europe of this idea of unmixing. His interesting monograph,[10] with numerous beautiful illustrations, seems most convincing to some students of ore deposits.

Lately, heating tests have been made by Wandke, Schwartz, Newhouse, Bateman,[11] and others. Such heating tests show conclusively that the intimate intergrowth of the two minerals will disappear at definite temperatures. It can frequently be brought back by carefully annealing the specimen.

The writer believes the following facts suggest replacement rather than unmixing as the probable origin of these intergrowths of niccolite and chalcopyrite from the Worthington mine. The intergrowths are practically confined to areas of niccolite surrounding grains of maucherite or gangue mineral. Where such

[8] Ransome, F. L., "Copper Deposits near Superior, Arizona," U. S. Geol. Survey Bull. 540, p. 152, 1911.

[9] Rogers, A. F., "Secondary Sulphide Enrichment of Copper Ores, with Special Reference to Microscopic Study," *Min. and Sci. Press*, vol. 109, p. 686, Oct. 31, 1914.

[10] Schneiderhöhn, H., "Anleitung zur Mikroskopischen Bestimmung von Erzen," Berlin, 1922.

[11] An extensive bibliography will be found in the paper by A. M. Bateman entitled: Some Covellite-Chalcocite Relations, ECON. GEOL., vol. 24, p. 424, 1929.

intergrowths occur in broad areas of niccolite not in contact with foreign minerals, there is a possibility that such foreign minerals may be beneath the present surface of the specimen or may have been immediately above, and were ground away in polishing the specimen. Veinlets of chalcopyrite occur within broad areas of niccolite, but they are rare. Such veinlets show ragged edges suggesting a replacement of the niccolite rather than simple fissure filling. Chalcopyrite can be traced from such intergrowths into grains of maucherite, and the veinlets always show smooth boundaries, indicating very little replacement of the maucherite. None of these veinlets of chalcopyrite in maucherite contain niccolite. One would naturally expect some niccolite if the texture is due to unmixing, as the chalcopyrite is only a minor constituent in these niccolite ores.

When a later mineral is introduced in an ore, the solutions are likely to enter along minute fractures or at the contact between two different kinds of minerals. Such contacts are probably a series of sub-microscopic cracks produced, perhaps, by the different rates of expansion and contraction of the two minerals.

SEQUENCE IN THE DEPOSITION OF THE ORES.

The writer is inclined to agree with Wandke and Hoffman [12] that the large ore bodies of the district were formed by hydrothermal solutions. The intense alteration of the wall rock surrounding the ore bodies in the greenstones on the deeper levels of the Creighton and also in the graywacke on the deeper levels of the Frood mine suggests such an origin. A quartz vein, nearly continuous and of variable width, seems to connect the two great lenses of ore on the 2,800 level of the Frood. Pyrrhotite and chalcopyrite occur in this quartz vein, and the wall rock adjoining the vein shows the same type of alteration associated with the main ore bodies. This alteration consists essentially of the development of hornblende and brown biotite, and occasionally actinolite.

A second stage in the deposition of the ores at Sudbury consists of the formation of veins along fractures in the massive

[12] Wandke, A. and Hoffman, R., "A Study of the Sudbury Ores," ECON. GEOL., vol. 19, pp. 199–203, 1924.

sulphides. The gangue minerals in such veins are quartz and a flesh-colored carbonate. At the Worthington mine these veins carry arsenides, and the order of deposition appears to be: gersdorffite, maucherite, niccolite, and chalcopyrite. Similar veins of quartz and carbonate occur at the Creighton and Frood mines. Chalcopyrite is the ore mineral, although some niccolite and maucherite was found in one of the veins at the Frood. Occasional fragments of pyrrhotite found in these veins are believed to have been detached from the wall (of massive sulphide) and enclosed in the vein filling. A vein of this type two inches wide was traced from where it cut the pyrrhotite-pentlandite-chalcopyrite ores into the wall rock for a distance of 30 feet along a crosscut to where it disappeared in one wall of the crosscut. Similar veins have been observed in the granite at the Creighton. The rock alteration associated with these veins is slight.

The last phase in the deposition of these ores is the formation of veins of sphalerite and galena. This type is relatively rare in the massive ore bodies. Polished surfaces of the massive sulphides frequently shows small amounts of both sphalerite and galena as rounded blebs. Such galena deposits as are shown on Colman's map of the district are quartz veins carrying pyrite, chalcopyrite, galena, and a little sphalerite. The zinc deposits in the Sudbury Basin belong to this stage in the deposition of the ores.

SUMMARY OF MINERALIZATION.

1st stage Magnetite, pyrrhotite pentlandite, chalcopyrite	High temperature hydrothermal
2d stage Gersdorffite, maucherite niccolite-chalcopyrite intergrowths	Moderate temperature hydrothermal
3d stage Pyrite, sphalerite galena	

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THE ORES OF THE NORTHERN RHODESIA COPPER BELT.

ALAN M. BATEMAN.

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INTRODUCTION.

THE new copper field of Northern Rhodesia gives promise of becoming the greatest individual copper mining center of the world. Within a space of hardly four years over 300 million tons of ore of better than 3¼ per cent. copper content have already been developed in this region and more reserves are being added monthly; the available tonnage may be more than doubled. A virgin bush country has been changed to one of industrial activity; towns are being built, plants are being reared, and branch railroads are intersecting the country. In from four to five years the region should be producing around 400 million pounds of copper; in ten to twelve years a production of 1,000 million pounds of copper annually is possible of achievement insofar as tonnage, grade of ore, mining and treatment conditions are concerned.

The part played by geology in this amazing development is the outstanding romance of modern economic geology. Probably in no other place is there a finer example of large-scale scientific prospecting for metals, in a region previously unknown geologically, that has been attended with such remarkable success. Great credit is due to the resident geologists and engineers who have by careful geological work deciphered the controls of the metallization and thereby laid the groundwork for the rapid exploration and development of the ore deposits.

The unique deposits themselves are of no less interest than their rapid development and the problems they raise attract the attention of all who have had the opportunity to study them. They present a new type among large-scale copper deposits and points of dissimilarity with the "porphyry coppers" are more numerous than are the similarities. Reliable information [1] about

[1] The best papers to date on the geology of the new copper belt are: "An Outline of the Geology and Ore Deposits of the N'Kana Concession," by Dr. Anton Gray, and "The Geology and Development of the Roan Antelope Mine," by D. C. Sharpstone, privately printed, London, May, 1929; "Notes on the General Geology of Northern Rhodesia," by J. A. Bancroft and R. A. Pelletier, Int. Geol. Cong. 14th Session, South Africa, Guide Book Excur. C–22, Pretoria, 1929; and "The Copper Deposits of Northern Rhodesia," by Anton Gray and R. J. Parker, *Eng. and Min.*

them is as yet all too scanty. An earlier paper [2] by the writer presented before the annual March meeting of the Canadian In-

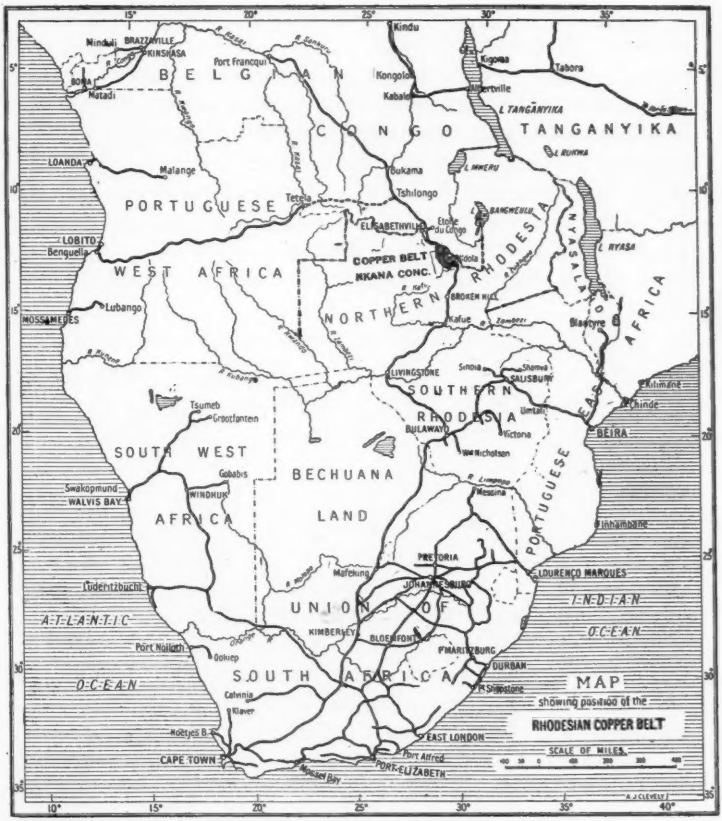


FIG. 1. Map showing location of the Copper Belt and N'Kana Concession in Northern Rhodesia (Courtesy Rhodesian Selection Trust, Ltd.).

Jour., vol. 128, 1929, pp. 384–389, 429–434, 470–472 (largely a reprinting of the first-mentioned article).

2 "The Rhodesian Copper Deposits," by Alan M. Bateman, *Bull. Can. Inst. of Min. and Met.*, pp. 477–513, April, 1930.

stitute of Mining and Metallurgy in Toronto treats of the occurrence and character of these deposits, chiefly for the interest of mining engineers. The following pages deal briefly with the geological setting [3] of the deposits and present further study upon the interesting ores.

The Rhodesian Copper Belt, if it may be so termed, lies in south-central Africa at about 12° 45′ South latitude. It forms a narrow strip along that part of Northern Rhodesia which lies adjacent to the province of Katanga in the Belgian Congo (Fig. 1). One may reach it by railway from Cape Town (2,159 miles), from Beira on the east African coast (1,472 miles), or by rail and water from Dar-es-Salaam, in Tanganyika. A new railroad will shortly be completed from Lobito Bay on the West Coast.

Physical Features of the Region.

The region forms part of a great plateau that lies at an elevation of about 4,000 feet. The flattish surface is broken here and there by widely separated shallow stream depressions or rare kopjes (hills) that form monadnocks on this slightly dissected peneplain. From the top of one of these kopjes one may gaze miles in all directions over a monotonously undulatory surface of acacia tree tops. The divide between the Congo and Zambesi drainages, which also marks the boundary between Katanga and Northern Rhodesia, in places can hardly be discerned by the eye.

The region is drained by the Kafue and its tributaries, a part of the Zambesi river system. The Kafue apparently follows its old pre-uplift course and it crosses the region without regard to the hardness or structure of the underlying rocks. Its valley is, in general, broad and shallow. Here and there it has entrenched its old meanders to form shallow but steep ravines. The tributaries likewise occupy broad, almost imperceptible valleys which are commonly swampy near their headwaters. The tributaries for the most part also flow transverse to the rock structure but in places they are subsequent streams, controlled by the strike of

[3] The general geology given here is largely abstracted from the above-mentioned paper.

resistant rocks. The region evidently has been uplifted in a late geologic period.

The surface is mantled by a deep regolith. Outcrops are few. Forests cover the land. Here and there open grassy areas (dambos) break the monotony of continuous bush. Underbrush is scanty and the trees are widely spaced so that the region presents the appearance of a great park. Travel through it is simple.

This is not a jungle region but semi-open plateau country, which despite its low latitude is healthful and pleasant to live in. It is amply watered with 40 to 50 inches of rainfall, which falls between November and April. During this rainy season the grasses grow luxuriantly and swamps and dambos become flooded; travel and field work are retarded. In the succeeding dry season (winter) continuous sunshine prevails, the days are pleasantly warm, the dambos dry up, small streams cease, the roads harden; transportation and field work go on apace. The nights are always cool, even in summer, and in winter they are unpleasantly chilly. Malarial mosquitoes breed in the rainy season but ordinary precautions prevent the contraction of fever. Their elimination from the vicinity of the mines is only a question of effort and time. Sleeping sickness is absent but the animal tsetse fly prohibits the presence of any domestic animals. The region is highly suitable to support the great mining center now opening up there.

Geologic Setting.[4]

Geologically similar conditions prevail throughout the copper belt. The ores occur in sedimentary beds underlain by metamorphic and intrusive rocks and overlain by a great thickness of alternating clastic sediments. There are later intrusions of granitic and gabbroic rocks. All the sediments are non-fossiliferous and appear to be continental in origin.

The paucity of outcrops and the deep regolith have imposed unusual difficulties in working out detailed areal geology. Never-

[4] The rock formations are only briefly outlined here. More detailed descriptions may be found in the papers listed under Footnote 1 and in the recent paper by the writer, *op. cit.*

theless, excellent work has been done to date by the resident geologists and engineers.[5] They responded to the stimulus of the necessity of a knowledge of the structure in order to guide mining exploration. Rapid and reliable methods were evolved. Sparse outcrops were supplemented by sinking hundreds of pits, 20 to 100 feet, to bedrock. Drill hole locations were indicated and results were checked with bore hole cores. The geologic map shown in Fig. 2 is the result of such work by the Rhodesian Selection Trust geologists. Areal mapping of extensive adjacent and more distant regions is being carried on, under the direction of Dr. J. A. Bancroft, by means of surface traverses.

The geologic column[6] established by the geologists of the Rhodesian Selection Trust under the direction of Dr. Anton Gray is as follows:

TABLE I.

GEOLOGIC COLUMN OF N'KANA CONCESSION.

IV. Acid and Basic Intrusive		
	Gabbro and diabase sills	
	Younger gray granite	
iII. System of the Katanga		
	Purple quartzite series	7,000 feet +
	Mutundo series	7,000–8,000 feet
	Glacio-fluvial series	500 feet + or —
	Christmas series	2,000 feet
	Roan series (Bwana M'Kubwa series)	3,000–4,000 feet
	Unconformity	
II. Granitic Intrusives		
	Muliashi porphyritic granite and gneiss	
	Older gray granite	
I. Basement Complex		
	Muva schists	
	Lufubu schists and gneisses	

The Older Formations.—The pre-Roan rocks (Fig. 2) consist of schists, quartzites, and gneisses which have undergone extreme

[5] Especial credit for this work is due to: Dr. L. E. Reber, former geologist at N'Changa; Mr. R. J. Parker, Manager, Dr. Anton Gray, Chief Geologist, and Dr. D. A. Davidson and T. F. Andrews (deceased), geologists of the Rhodesian Selection Trust; Dr. J. A. Bancroft, Chief Geologist of the Rhodesian Anglo-American; and D. C. Sharpstone, Chief Geologist of the Roan Antelope Mine.

[6] Gray, Anton, *op. cit.*, p. 12.

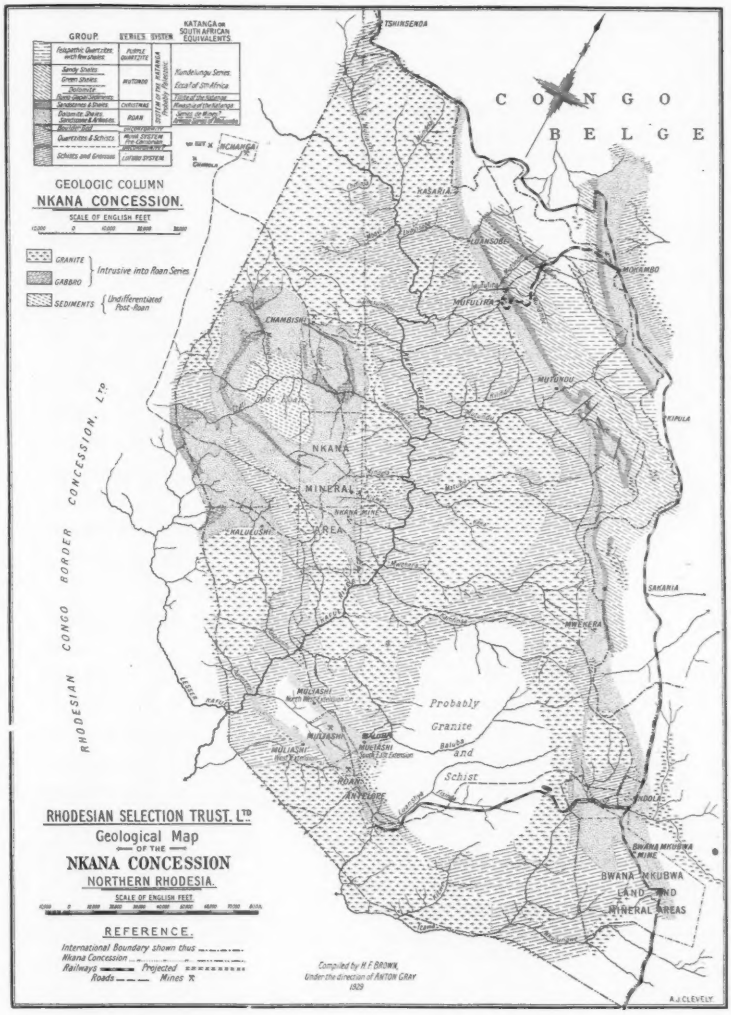


FIG. 2. Geological map of the N'Kana Concession, Northern Rhodesia, made under the direction of Dr. Anton Gray (Courtesy Rhodesian Selection Trust, Ltd.).

metamorphism and have not been differentiated in field mapping. These have been intruded by the older gray granite and the Muliashi granite,[7] which are older than the Roan series. These older rocks are thought to be pre-Cambrian in age.

Roan Series.[8]—This is the important formation of the region, for it is the host rock of the copper. It receives its name from the Roan Antelope Mine. The lower Roan consists of conglomerates, arkoses, feldspathic quartzites, argillaceous sandstones, dolomitic shales, and dolomite; the total thickness varies greatly, but attains 1,500 feet. The ore is confined to this lower part. The upper Roan consists of 1,500 to 2,500 feet of dolomitic shales, argillaceous sandstones, and dolomite. These beds may correspond to the ore-bearing Série des Mines of Katanga.

Later Formations.—The post-Roan-sediments (Fig. 2) have been separated by Dr. Gray[9] into the formations listed in Table I. None of these are known to be metallized save for traces of copper and locally abundant pyrite in certain "oölitic" quartzites of the Christmas series.

The Christmas series consists of 2,000 feet or more of shales with some interbedded "oölitic" quartzites and a 50-foot bed of conglomerate at its base.

The Mutundo and Purple quartzite series attain 14,000 to 15,000 feet in thickness and together are considered to be the equivalent of the Kundelungu series of the Congo. They are non-fossiliferous and are apparently of continental origin. At the base is a prominent conglomerate upwards of 500 feet thick, which is considered by the Rhodesian Selection Trust geologists to be of glacio-fluvial origin. Some of the pebbles are angular and striated and look like glacial pebbles. Dr. Gray thinks this bed may be the equivalent of the so-called "Tillite of the Katanga." Above it are shales and a dolomite (1,000 feet) which passes upwards into dolomitic shales 4,000 to 5,000 feet thick. The 7,000 feet or more of overlying argillaceous sand-

[7] These two granites have not been found in contact. They may be gradations of the same intrusive, as is thought by Dr. Bancroft (*op. cit.*, p. 24).

[8] This is the same formation that Dr. Bancroft calls the Bwana M'Kubwa series.

[9] *Op. cit.*, p. 21.

stones and quartzites are bluish and purplish in color and are characterized by pronounced rhythmic banding. These are the youngest consolidated formations in the copper belt.

Later Intrusives.—Gray granite intrudes the ore beds at the Roan, N'Kana, Mufulira and Chambishi mines and a red granite which may be part of the same intrusive cuts the N'Changa ore beds (Fig. 2). The gray granite is considered to be responsible for the copper mineralization in Rhodesia; consequently it is of considerable economic interest. In places, as at Muliashi, the granite intrusion has intensely metamorphosed the ore beds to an aggregate of amphibole, chlorite, tourmaline, and other minerals.

A similar granite intrudes the Série des Mines in Katanga, where it has produced tourmaline and cyanite in the dolomitic shales.

The areal distribution of the granite over the copper belt suggests a slightly eroded granite batholith with pendants of sediments projecting deeply into the granite and cupolas of granite penetrating the sediments. Erosion just truncated the upward granitic projections but not deeply enough to remove the downfolded synclinal areas of sediments. Consequently, numerous "windows" of granite appear in the region.

There are also numerous sill-like intrusions of basic rock with gabbroid to diabase texture within the Roan series. These intrusions appear to be later than the folding that affected the sediments and, at Kalulushi, have metamorphosed the Roan beds.

Unconsolidated Deposits.—The region is mantled with unconsolidated deposits that range in thickness to over 100 feet. For the most part they represent the decomposition products of the underlying bed-rock. They are sandy or clayey. Humus is scarce. Here and there are areas of impure iron oxide of lateritic derivation, but they are not true laterites.

Some peculiar, sub-angular, polished and pitted pebbles occur in the regolith a few feet beneath the surface, and in flat areas remote from stream channels. They are typical of pebbles that have been polished and pitted by wind-blown sand in arid regions, and this strongly suggests that arid conditions prevailed in this region not very long ago.

An interesting feature is that certain plant forms are restricted to the soil cover overlying certain formations, and the recognition of these enables the formations to be approximately delimited and test pits to be more accurately located.

Age of Formations.—Workers in Central Africa have faced the baffling problem of trying to determine the age of great thicknesses of non-fossiliferous formations. No age relations have been definitely established for the formations described nor for the adjacent Katanga formations. The pre-Roan rocks have been thought to be pre-Cambrian.

The Roan series lies unconformably on the underlying rocks. Dr. Bancroft groups it under the pre-Cambrian [10] and says it may possibly be equivalent in age to the Lomagundi series of Southern Rhodesia.[11] Gray and Sharpstone consider that it may be Paleozoic.[12] The geologists of the Union Minière de Haut Katanga also think it may be Paleozoic.[13] This assumption of age, however, rests on a long range and uncertain correlation of the overlying Tillite of the Katanga with the Dwyka tillite of Permian age in South Africa. Dr. Bancroft [14] points out, however, that this seems an unwarranted conclusion and that P. Fourmarier's correlation with the Waterburg of South Africa seems more probable. My own observations do not suggest a similarity between the "Tillite of the Katanga," the glacio-fluvial conglomerate of the Rhodesian Copper Belt, and the Dwyka tillite. Rather, the northern formations have more lithological resemblance to the tillite in the Pretoria series of the Transvaal system, south of Pretoria. Van Doornick [15] concludes that the Katanga mineralization is early Paleozoic and thinks the Katanga tillite may correspond with the Transvaal system, although his reasons for so stating are not clear.

[10] *Op. cit.*, p. 3.

[11] *Op. cit.*, p. 7.

[12] Int. Geol. Cong., XV Sess., So. Africa, Guide Book, Exc. C–22, Pretoria, 1929, p. 34.

[13] Personal communication from H. J. Schuiling.

[14] *Op. cit.*, p. 10.

[15] Van Doornick, N. H., Doctorate thesis (in Dutch). G. Naeff, The Hague, 1928. Reviewed by E. M. Bunge (in French), *Revue de Geologie*, vol. 10, 1929, pp. 126–129.

As the writer recently pointed out,[16] a new light may now be thrown on this knotty problem of age determination. The radium deposits of Chinkolobwe, Katanga, have been determined on the basis of radio-active disintegration, to be 665 million years old.[17] According to Professor Adolph Knopf [18] this places them in the late pre-Cambrian. Consequently the beds of the Série des Mines in which the uranium deposits are reported to occur must be of even earlier pre-Cambrian age. Inasmuch as the Katanga primary copper metallization seems definitely associated with the granite [19] and the copper and uranium metallization appear to be of one age, it follows that the copper ores of Katanga are also of pre-Cambrian age.[19a]

If, then, correlation can be established between the copper ores, granite, and ore beds, of Katanga and of the Rhodesian Copper Belt, then the age of the Roan ore beds might be fixed. First, as will be shown later, the copper sulphides of Rhodesia and Katanga evidently belong to one metallogenetic epoch. Second, the later granite of these two adjacent areas appears to be part of the same underlying mass. The same granite exposure extends on both sides of the boundary near Tshinsenda (Fig. 2); the metamorphism it has produced is similar in both regions; and the primary metallization appears to be associated with it in both regions. Third, the correlation of the ore beds in Katanga and Rhodesia is controversial. The Katanga ore beds may be of the same age or slightly older than the Roan, as thought by some geologists, or they may represent the upper part of the Roan, as Dr. Gray thinks, and as I am inclined to think from a brief investigation of the two regions. In any case, their ages are not widely separated.

Although the chain of evidence is admittedly weak in places, there is a strong suggestion that the ores, the later granite, and

[16] Bateman, Alan M., "The Rhodesian Copper Deposits," *Bull. Can. Min. and Met. Inst.*, April, 1930, pp. 477–513.

[17] Davis, C. W., *Amer. Jour. Sci.*, vol. XI, p. 217, 1926.

[18] Personal communication. A revised computation by my colleague, Professor Knopf, who called my attention to the matter, gives 610 million years.

[19] Conclusion from personal observations.

[19a] Schoep, A. (*Ann. de la Soc. Géol. de Belg.*, 49, 1926, p. 2) reports linnaeite in the pitchblende. This establishes kinship between the pitchblende of Katanga and the linnaeite-bearing copper ores of Rhodesia.

the ore beds of both regions are of the same age and, therefore, the Roan series is of pre-Cambrian age. This evidence, although not so conclusive as might be desired, is unquestionably the strongest that has yet been advanced for the solution of this knotty problem of the age of the Roan series and the copper deposits.

Structure.—The sedimentary rocks have been strongly folded into a series of asymmetric anticlines and synclines (Fig. 2) whose axes trend generally northwesterly and plunge in the same direction. The folds are in general simple and open so that the dips of the limbs are mostly less than 50°; at Roan and Bwana there are 90° dips (Fig. 4). A few minor cross folds occur.

The sedimentary rocks have been largely cut away from the anticlines and only the lower parts of the down-folded synclines have been left to outcrop on the flattish peneplained surface. The post-Roan rocks are preserved only in the large synclines (Fig. 2) and the pre-Roan rocks mostly occupy the centers of the eroded anticlines. Since the folds pitch northwesterly, the ore beds in the synclines outcrop in the form of V's whose closed ends point southeasterly (Fig. 3). Individual ore beds thus become progressively deeper toward the northwest.

Several faults are known to occur but the fault structure has not been entirely deciphered as yet.

The intrusion of younger granite appears to have been contemporaneous with or to have followed slightly later than the folding.

THE ORE DEPOSITS.

The amazingly rapid development of this district has resulted already in seven proven mines, namely: Roan Antelope, N'Kana, Mufulira, Chambishi, N'Changa, West Extension, and Bwana M'Kubwa. In addition, the Baluba and Chingola prospects will probably develop into mines.[20] There are also other prospects of promise. Five of these properties lie within the boundaries of the N'Kana Concession; the others are adjacent (Fig. 2). As the properties are still in progress of development, complete

[20] The Mufulira, Chambishi and Baluba belong to the Rhodesian Selection Trust; the N'Kana and Bwana to the Bwana M'Kubwa Copper Mining Co.; and the West Extension and Chingola to the Rhodesian Congo Border Concession, Ltd.

geological information about the deposits is not yet available. Much of the information regarding the ore has been obtained from drill-hole cores. Consequently, later work may cause some of the statements here given to be modified.

Character of Deposits.—All the deposits of the Copper Belt [21] are, in general, similar in character, save for the old Bwana mine. They consist of one or more beds of the Roan series that have become fairly uniformly metallized with minute specks of the

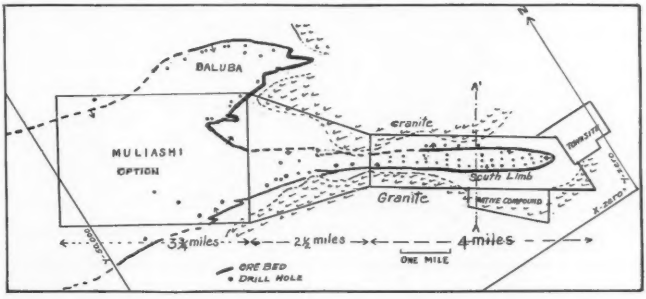


FIG. 3. Sketch plan of Roan Antelope ore bed on Roan Antelope (enclosed area) and Baluba properties; adapted from D. C. Sharpstone (Courtesy Rhodesian Selection Trust, Ltd.).

copper sulphides, chalcocite, bornite, and chalcopyrite. Most of the deposits are sulphide ore; some are oxidized. The deposits all lie within 1,500 feet of the base of the Roan series; most of them are within 500 feet of the base. Consequently, their position is determined by the stratigraphic horizon and their shape by the character of the folding. Where the ore beds are in narrow pitching synclines, as at Roan and N'Changa, the deposits form parts of one or both limbs and have, in plan, the form of a horizontal V (Fig. 3) and in cross section that of a distorted U (Fig. 4). Where the deposits are on one limb only of large synclines, as at Mufulira, Chambishi, N'Kana, and Bwana, they have the form of tabular lodes (Fig. 5).

[21] Detailed descriptions of the individual mines will be found in the paper by Dr. Gray and Mr. Parker, *op. cit.;* and in the Guide Book by Dr. Bancroft and Mr. Pelletier, *op. cit.*

At most of the mines the ore so far disclosed is confined largely to one bed. But at N'Changa there are two separate metallized beds known as the Dambo and River lodes. These,

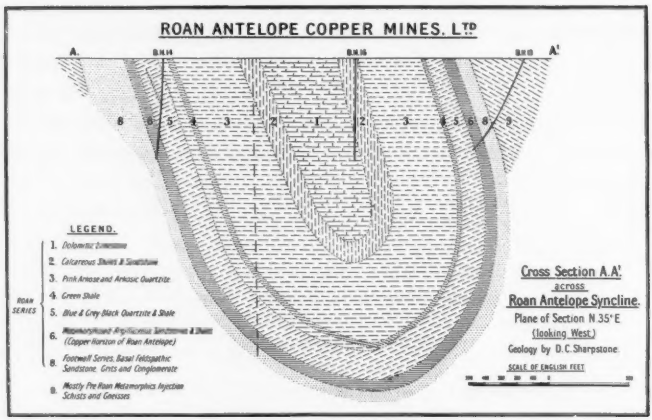

ROAN ANTELOPE COPPER MINES. LTD
A
A'
LEGEND.
1. Dolomitic Limestone
2. Calcareous Shales & Sandstone
3. Pink Arkose and Arkosic Quartzite
4. Green Shale
5. Blue & Grey Black Quartzite & Shale
6. (Copper Horizon of Roan Antelope)
7. Footwall Series. Basal Feldspathic Sandstone, Grits and Conglomerate
8. Mostly Pre Roan Metamorphics Injection Schists and Gneisses
ROAN SERIES
Cross Section A.A'
across
Roan Antelope Syncline.
Plane of Section N.35°E
(looking West)
Geology by D.C.Sharpstone.
SCALE OF ENGLISH FEET

FIG. 4. Section along *A–A'* of Fig. 3, Roan Antelope Mine (Courtesy D. C. Sharpstone and Roan Antelope Copper Mines, Ltd.).

however, lie on opposite limbs of the syncline and as yet have not been found to be metallized on the same limb directly over each other. At Mufulira there are three separate lodes one

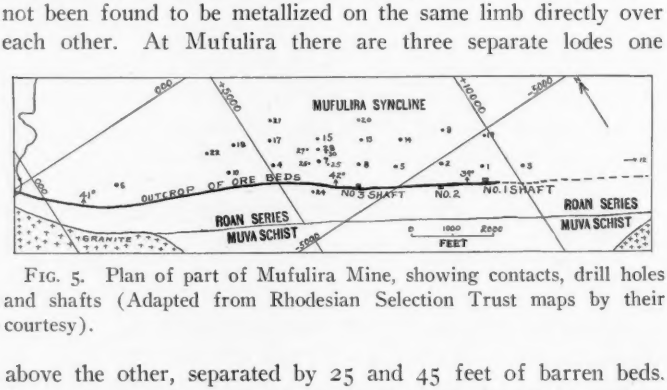


FIG. 5. Plan of part of Mufulira Mine, showing contacts, drill holes and shafts (Adapted from Rhodesian Selection Trust maps by their courtesy).

above the other, separated by 25 and 45 feet of barren beds. But in the northeast part of the deposit these three lodes coalesce to form one ore body, which is over 100 feet thick in places.

This mine is an exception in that the metallization breaks across from one bed to the other.

It is not the same bed that is metallized in each mine. The individual ore beds of the different mines lie at slightly different horizons and differ in composition. The host rock at the Roan is a dense compact dolomitic argillite; at Mufulira it is feldspathic quartzite, arkose, and graywacke; at N'Kana and Chambishi it is an argillaceous sandstone or shale.

An outstanding feature of the deposits is the persistence of the metallization and the remarkably uniform width of the ore over great horizontal distances. For example, at the Roan, continuous ore has been disclosed by workings or numerous drill holes for 12,000 feet along the north limb, around the nose of the syncline, and for 16,000 feet along the south limb. A further extension of 22,000 feet of ore has been shown by widely spread bore holes. Thus along one limb there is 7½ miles of practically continuous ore in the Roan shale which averages 3.3 per cent. copper over a thickness of 25 to 30 feet.

The ore itself is deceptive looking material. The Roan ore looks like ordinary rock; the copper sulphide specks become evident only upon close inspection. The ore in the other sulphide mines is of somewhat larger grain and more nearly resembles the disseminated sulphide ore of the "porphyry copper" deposits. The ore minerals occur chiefly as disseminated discrete grains; veinlets and blebs are rare. Few grains are greater than 2 mm. in diameter; many are as small as 0.0001 mm. The average size of the Roan sulphide grains is about 0.2 mm. and of the Mufulira, about 0.75 mm. The specific gravity of the Roan ore is 2.8.

The size of the deposits and the tonnage and grade of the ores of the important properties are shown in the accompanying Table II. These figures are not final; they are constantly being revised with continuing development and therefore reflect conditions only at the time of writing. The lengths are being increased, and new drill holes are revealing deeper ore. The figures of tonnage are those that have been officially or semi-officially reported and are much smaller than the actual tonnage known to be present. Over 300 million tons of ore of better than 3¼ per

cent. copper are now proven; two to three times this tonnage will unquestionably be developed. It is evident that these deposits will rank among the most important copper deposits of the world.

TABLE II.

APPROXIMATE DIMENSIONS, TONNAGE, AND GRADE OF COPPER ORES OF THE RHODESIAN COPPER BELT.

Mine.	Length in Ft.	Thickness.	Depth to Date.	Millions of Tons.	% Copper.
Roan Antelope	50,000	25	2,086	75	3.3
Mufulira	7,000	70–90	1,527	60	4.5
N'Kana	14,000	31	2,279	75	4.2
N'changa	12,000	85	1,040	59	3.5
Chambishi	5–6,000	30	800	20	3.0
W. Extension	8,000	100	1,343	50	8.5
Bwana M'Kubwa	1,800	80	400	4	3.4

Distribution of Ore.—The ore beds are remarkably uniformly metallized and are sharply delimited against barren hanging and foot walls. Gradational contacts, as in the case of the " porphyry copper " deposits, are practically non-existent.

The particles of ore minerals are commonly scattered without arrangement throughout the ore beds, but in the shales there is a tendency for them to be aligned along the shale partings or, in part, to take the form of minute parallel threads.

The individual copper sulphides appear to be rather haphazardly distributed. There appears in general to be more bornite and chalcopyrite in the deeper parts of the bore holes and more chalcocite in the copper parts. However, ore exposures are too meager as yet to indicate that there is a general and progressive change downward from chalcocite to bornite and chalcopyrite. In the Roan mine there appears to be a progressive change horizontally from dominant chalcocite at the easterly end to bornite and chalcopyrite farther westward. There is also a suggestion that chalcopyrite is proportionately greater in amount near where granite intrudes the ore beds. I obtained the impression that there might be, in the region, a horizontal or inclined zoning of sulphides within a bed—a distribution suggestive of primary zoning outward from intrusive granite centers.

Oxidation.—Most of the large deposits consist of sulphide ore. This applies to the Roan, Mufulira, N'Kana, Chambishi and Baluba. The N'Changa and West Extension ore is three-quarters to four-fifths oxidized. The old Bwana mine has been struggling for several years with relatively low-grade, completely oxidized ore.

Oxidation of all the deposits is universal above the ground water level, which ranges from 0 to 200 feet. At the Roan, oxidation is complete down to 100 feet and a considerable proportion is oxidized down to 200 feet. Similar conditions prevail at Mufulira. Commonly, this upper oxidation is complete; all the sulphides have been oxidized. Most of such copper has remained in the oxidized zone in the form of copper carbonates or chrysocolla and the grade of the oxidized ore in general differs little from that of the sulphide ore. The transformation from sulphide to oxidized copper compounds seems largely to have taken place *in situ* without appreciable migration of the copper in solution. In several places, however, the copper has been completely leached from the oxidized zone—only a barren cropping or gossan remains.

In the case of the deposits that are largely oxidized the oxidized compounds occupy the former site of the parent sulphides, and in addition there has been considerable migration of copper and its redeposition in the form of oxidized copper minerals. There has also been, in places, considerable oxide enrichment of copper. The very rich carbonate ore of the N'Changa West Extension (R. C. B. C.) must represent a considerable local concentration of copper by deposition of oxidized copper compounds that have been transported in solution from other parts of the zone of oxidation. In all the deposits azurite is remarkably scarce; malachite is the predominant copper carbonate.

The minor proportion of oxidized ore in the Rhodesian Copper Belt is in marked contrast to the adjacent Katanga section, where the commercial copper ores are entirely oxidized.

Throughout the sulphide mines there is a small amount of erratic and deep oxidation that reaches to a depth of several hundreds of feet beneath the water table. It may be sparsely

disseminated, as at Mufulira, or fitfully distributed, as at the Roan, N'Kana, and Chambishi, where local oxidized ore may occur in the midst of, or even may underlie sulphide ore. This peculiar distribution is due apparently to structural control. With inclined beds of varying perviousness, oxidizing waters have moved down the dip of the more permeable ones. If these happen to lie at the base of the deposit, then deep oxidation of the sulphides in the lower beds could take place while overlying metallized beds may escape oxidation. Thus, local pockets of oxidation would result at the base, or in the middle of sulphide beds.

The cause of this deep oxidation in both the sulphide and the oxidized deposits so many hundreds of feet beneath the water table is an interesting problem. Oxidation far beneath the water table in a flattish peneplained region with relatively stagnant ground water, is unusual. Oxidation normally does not take place beneath the water table, where ferrous salts prevail. Either, the water level at one time must have stood hundreds of feet lower and has since been raised relatively to the ore deposits, or, oxidation must have gone on beneath the water table as a result of a deep and rapid artesian circulation by means of which entangled and dissolved oxygen was carried far below the surface. The latter seems improbable, since a deep and rapid artesian circulation implies considerable difference in relief. Relief is negligible and low outlets are lacking, nor do they appear to have been present in the recent geologic past.

A change of water level seems the most likely explanation. Three ways (Figs. 6, 7, 8) may generally be considered to account for such changes of water level: (1) Preëxisting deep and steep valleys whose bottoms determine the position of the adjacent water table (Fig. 6-*a*) may become filled up by later sediment, thus raising the local water table and submerging the preexisting oxidized zone (Fig. 6-*b*). (2) A deep oxidized zone originally high above the water table (Fig. 7-*a*) may become down-faulted and submerged beneath the water table (Fig. 7-*b*). (3) Deep oxidation may have taken place during a previous arid climate with low water table (Fig. 8-*a*) and a subsequent climatic

change may have raised the water table, submerging the oxidized zone (Fig. 8-*b*). Of these, the first seems improbable in Rhodesia inasmuch as there is no evidence of deep valleys and filling by late deposits. Neither is there any evidence of the faulting, such as would be required by the second explanation, although it

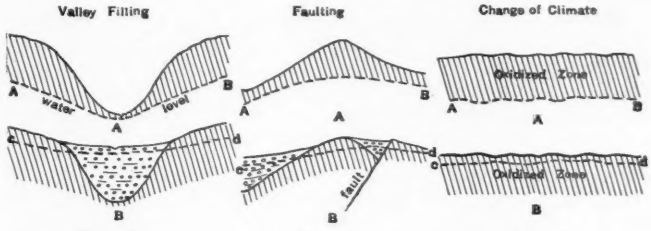


FIG. 6. FIG. 7. FIG. 8.

FIGS. 6, 7, 8. Diagrams illustrating three methods by which oxidized zones may become submerged below the water level. *A*, before; *B*, after. *A–B*, bottom of zone of oxidation at previous water levels. *C–D*, raised water level. Diagonal lines, oxidized zones.

is possible such faulting might be hidden. The third explanation, namely, an earlier deep water level during a preceding arid period, seems the most likely explanation and finds some support in the character of the soil and in the occurrence of the subangular polished and pitted wind-worn pebbles in the soil, previously referred to. Moreover, such desert conditions now prevail in the Kalahari Desert to the south, and Maufe [22] concludes that the Kalahari Desert sand once extended over parts of Southern Rhodesia. Likewise, Dr. Bancroft states [23] that during a recent period in the history of Northern Rhodesia the "climate was more arid than now."

During such an arid period the water level was probably deep and irregular and fitful oxidation penetrated deeply. The paucity of rainfall did not allow of complete oxidation save in low-lying places, such as around N'Changa, where there would tend to be a concentration of the infrequent rainfall.

[22] Maufe, H. B., "Some Problems in So. Rhodesian Physical Geology," *S. African Jour. of Sci.*, vol. 24, p. 34, 1927.

[23] *Op. cit.*, p. 28.

This arid condition with its attendant deep oxidation probably existed when the peneplain lay at a lower level than at present. The (recent) uplift of the peneplain to its present 4,000-ft. elevation probably inaugurated the present humid climate during which the water table became gradually raised until it submerged deeply the oxidized zone.

This hypothesis supplies a ready explanation for the great depth of the oxidation and for its wide yet capricious distribution. It also renders understandable certain features of the secondary sulphide enrichment to be discussed later.

Surface Indications of Ore.—Surface expressions of these great deposits are scarce. Nevertheless, most of the large deposits outcropped in at least one place and this led to their discovery and development. These croppings had been known and worked in a crude way by the natives before the advent of the white man.

The deciphering of the sequence of beds and the structure led to the projection of these croppings and yielded locations for exploration by drill and pit. In this way the deposits were extended far beyond the croppings. Still other valuable deposits [24] with no surface croppings were discovered through detailed geological work by unfolding the stratigraphic section and structure and then testing designated places by pit or drill. Several prospects indicated by these means are now being explored.

The surface indications of ore consist of croppings with copper, croppings without copper, copper springs, and " dambos."

The croppings with copper are short exposures of ore beds that contain malachite, chrysocolla, occasional cuprite or native copper, and, rarely, a speck or two of sulphide. The copper content of these runs from 1 to 4 or more per cent. In most of the croppings examined the copper minerals, particularly the carbonates, are susceptible of determination as to whether they are indigenous and therefore formed *in situ* directly from sulphides, or whether the rock was originally lacking in sulphides and the copper carbonates have been transported from elsewhere. The latter need not indicate the presence of ore beneath. The

[24] For example, the Mindola, Chingola, Baluba, and W. Extension, ore bodies.

character of much of the host rock is such that the copper has become fixed as oxidized minerals at or near its source, and little migration has occurred. Copper does not migrate far in the oxidized zone in the presence of carbonate and feldspars.

The croppings of ore beds without copper may represent parts that either were originally barren or have been leached of their original sulphide content. The two classes can be readily distinguished. The removal of the sulphides has left certain distinguishing features that can be deciphered with fair accuracy and there is no difficulty in determining beds that were originally metallized. The nature of the cavities left by the sulphides, the presence or absence of limonite, and the character and arrangement of the limonite, indicate the extent and, in general, the mineralogical content of the croppings before leaching occurred. First, a careful examination was made of the croppings that overlie ore of known mineralized character. Type croppings were distinguished, characteristic of the oxidation residues of chalcocite, pyrite, and of bornite and chalcopyrite, for the conditions that pertain in this particular locality. With these types in mind, inferences were drawn as to the probable mineralogical character of untested beds whose outcrops were available for inspection. In this way, barren croppings which might, and those which might not, be expected to have copper ore beneath them, were indicated. The cavities of sulphide derivation in the croppings of these ore beds are of course of minute size because of the extremely small diameter of the original sulphides. But with the aid of a powerful hand lens or a binocular microscope they can be readily deciphered. The interpretation of leached croppings in this region is unusually simple.

Copper springs or seeps are found in several of the low-lying dambos. They carry and deposit copper either as native copper or as oxidized compounds. They indicate of course that copper is present, but as the copper is in solution, it may have been transported considerable distances from its source, and therefore be no indication of the immediate presence of ore.

The much referred to "copper dambos," or open stretches in the bush where trees do not grow, supposedly because of the

presence of copper salts, were early heralded as indicating outcrops of copper lodes. This idea received its conception and impetus because a wide opening in the bush coincided for several thousand feet with the curved nose and adjacent limbs of the Roan Antelope deposit. In fact, this feature first suggested its true synclinal nature. Dambos were eagerly sought and airplane flights were made to detect them, but no other deposits were found by this type of indication. Dr. Gray and Mr. Parker [25] point out that dambos occur over rocks that contain no copper; and that over the rich Mufulira deposit there is no sign of any open space. They consider, therefore, that dambos are no reliable indication of copper ore.

THE ORES.

The sulphide ores consist of few and simple ore minerals, arranged in a hit or miss fashion through the containing rocks. Their size and distribution has already been referred to. Only the sulphide ores will be referred to here, since they are the most important, and the oxidized ores, already considered, have been derived by alteration from them.

Metallic Minerals.—The metallic minerals so far recognized in the copper belt are chalcocite, bornite, and chalcopyrite, which constitute the economic minerals in the order of importance as named. In addition there are extremely minor amounts or traces of pyrite, linnaeite (Co_3S_4),[26] covellite, native copper, zincblende, hematite, and magnetite. There are also minute specks of two undeterminable metallic minerals. One of them resembles tetrahedrite.

Oxidation Minerals.—The oxidation products that have been recognized are malachite, azurite, chrysocolla, cuprite, tenorite, native copper, cobalt, and manganese wad, goethite, hematite, and jarosite. The dark-blue copper phosphate, cornetite, has been found at Bwana M'Kubwa [27] and libethenite ($4\ CuO.P_2O_5.H_2O$) has been mentioned by Dr. Gray.[28]

[25] *Op. cit.*, p. 431.

[26] The identification of this mineral was kindly checked for me by Dr. M. N. Short of the U. S. Geological Survey, who found that it is unusual in that it contains no nickel whatever.

[27] Bancroft, J. A., *op. cit.*, p. 20.

[28] *Op. cit.*, p. 34.

Gangue Minerals.—Few gangue minerals have been introduced. A little introduced tourmaline in not uncommon and small amounts of quartz and carbonate occur in the form of microscopic veinlets. The gangue material is, therefore, the altered enclosing rock.

Host Rocks.—The host rocks of the ore minerals are all clearly sedimentary rocks of the Roan series. The granite is not known to be metallized. Pegmatite veinlets consisting of large crystals of quartz, orthoclase, and muscovite, with chalcocite, bornite, and quartz stringers, are rather common in the footwall rock of the Roan ore beds.

The host rocks have all undergone some alteration, which was apparently a part of the metallization. The arenaceous and arkosic sediments at Mufulira have been partly silicified and altered to quartzites. The sandy dolomitic shale or argillite of the Roan and Chambishi has also been lightly metamorphosed.

Some silica was introduced, and this shows up as a cement, in growths around older quartz grains, and in the form of minute quartz veinlets. Secondary feldspar has been found in growths around original feldspar granules. A little carbonate has been introduced. Some sericitization has taken place in addition to that originally present. A striking feature is the addition of tourmaline, partly by replacement of the matrix and partly by growths on pre-existent detrital tourmaline grains. Around Muliashi there has been some intense metamorphism of the Roan shale. The ore beds have been altered to a coarsely crystalline rock consisting largely of tremolite, garnet, chlorite, a brownish fibrous amphibole, and tourmaline.[29] Some of this material (Bore Hole M. O. 8) is excellent ore containing bornite, chalcocite, and linnaeite, which appear to be later than the metamorphic silicates. At Chambishi, also, there has been some metamorphism of the ore shale. At Mufulira there are some cherty rocks that appear to be silicified dolomites or limestones.

All these features mean that the rocks have been subject to heat alteration, presumably by hot solutions, and that substances have been introduced from extraneous sources and under fairly high

[29] No thin section is available of this material.

temperature, as is attested particularly by the tourmaline. This suggests a magmatic origin. A further study of the occurrence of the tourmaline would prove of interest. It might disclose a distributional relationship to the intrusives.

Detailed Discussion of Ore Minerals.

During the field work, suites of specimens were personally collected for later laboratory examination. About a hundred or so representative sulphide ore specimens have been polished and studied by means of the reflecting microscope, utilizing polarized reflected light. The apparatus used in this laboratory has previously been described.[30] The following remarks deal with the field and microscopic relationships of the individual sulphides as disclosed in the specimens examined.

Linnaeite (Co_3S_4).—This rare cobalt sulphide has now been noted in the N'Kana, Roan, Chambishi, and Baluba mines. It also occurs in the sulphides that underlie the oxidized ores of Katanga. At the N'Kana mine it is sufficiently abundant to give the ore a content of 0.02 to 0.46 per cent. cobalt.[31] It occurs in grains with square outlines suggesting cubes or octahedrons, and as grains of more or less rounded outline, up to 8 mm. in diameter. It clearly replaces the rock silicates and, judging from the accompanying metamorphosis of the inclosing rock, it represents a fairly high temperature phase of the metallization. The individual grains cut sharply across many smaller grains of rock silicates and include numerous unreplaced residuals of the latter. They also include rounded blebs of bornite and chalcopyrite, and the latter in turn holds inclusions of an undeterminable grayish mineral. With the high powers of oil immersion lenses, the linnaeite is seen to contain innumerable minute veinlets, about 1/25,000 of an inch in width, composed of bornite, chalcopyrite, and chalcocite, singly and together. These occupy parting planes and fractures in the linnaeite (Fig. 9).[31a] Hundreds of them occur

[30] Osborne, F. F., ECON. GEOL., vol. 23, p. 445, 1928.

[31] Bancroft, J. A., *op. cit.*, p. 27.

[31a] The writer wishes to acknowledge his indebtedness to Professor L. C. Graton of Harvard University for his kindness in making most of the photomicrographs used in this paper.

in a grain 5 mm. in diameter. The included bornite and chalcopyrite, and as far as can be determined, the chalcocite also, appear to be of simultaneous age, and all are clearly later than the linnaeite. Some rounded blebs of bornite and chalcopyrite, not

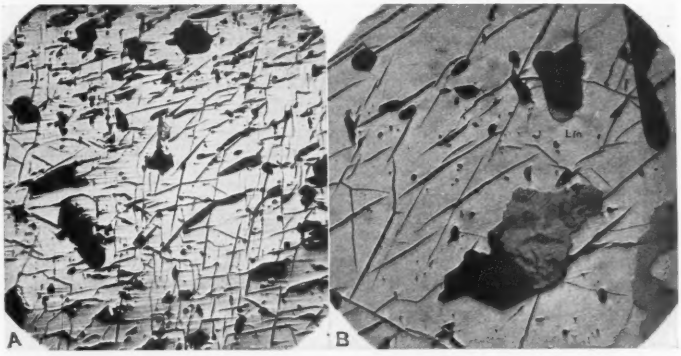


FIG. 9. Linnaeite intersected by veinlets of bornite, chalcopyrite, and chalcocite with inclusions of gangue (black) and chalcopyrite. Baluba mine. *A*, × 80; *B*, same × 175. Note in *B* inclusion of chalcopyrite containing inclusion of tetrahedrite (?).

connected with visible veinlets, may be inclusions of earlier age than the linnaeite. The linnaeite was among the earliest sulphides to form.

This linnaeite, as has been noted, is unusual in its freedom from nickel. It is more than a coincidence that some of the Katanga linnaeite shows similar microscopic characteristics with the Rhodesian linnaeite.[31b]

Pyrite.—This mineral was observed in only one or two ore specimens. It is almost absent from the main ore beds, though locally it is relatively abundant in certain of the higher formations, and in the upper beds at Baluba and Chambishi. The mineral has been introduced and is in part older than, and in part contemporaneous with, chalcopyrite.

Chalcopyrite.—This mineral is a minor though important constituent of the ores disclosed to date. It ranks third in abun-

[31b] Schoep (*op. cit.*) reports that the Katanga linnaeite from pitchblende ore contains nickel, gold, and selenium.

dance of the sulphides. It is clearly a hypogene mineral that has been introduced into the sediments subsequent to their formation and compaction. It truncates sharply, and without discrimination, adjacent grains of quartz and feldspar and replaces these and the other rock-forming minerals. It is prominently anisotropic under polarized light. It occurs as (*a*) small discrete grains of pure chalcopyrite; (*b*) in thread-like veinlets of pure chalcopyrite, parallel to the bedding or cleavage, and in places cutting across the cleavage of the metamorphosed shale (Roan); (*c*) in intergrowths of contemporaneous deposition with bornite, and in one specimen, with sphalerite; (*d*) as rare spines of microscopic size at the contacts of bornite that is undergoing replacement by chalcocite. The chalcopyrite fills vugs in some of the microscopic quartz veinlets and therefore is later in age than the introduced quartz. It crosses some of the secondary mica of the Roan shale, therefore is later in age than the metamorphism (and folding) of the shale. It started to form before the final deposition of the pyrite and continued to be deposited after the initial deposition of bornite. Consequently, some of it is earlier than, and some is contemporaneous with, the bornite. This mineral was not observed to replace any other sulphide except linnaeite.

Bornite.—This copper mineral is next in abundance to chalcocite in the specimens examined. However, it is possible that deeper workings of the future may disclose that it is even more abundant than chalcocite. In the deeper drill holes to date, it is more abundant than in the shallower ones. The bornite cuts across, expands into, and replaces the rock silicates. Its relation to the ore minerals is identical with that of chalcopyrite. If the latter is hypogene, so is the bornite. It clearly has been introduced and formed as an initial deposition by replacement of rock silicates.

Some of the bornite is extremely unusual. Bornite, being isometric, is normally isotropic with reflected light under crossed nicols. But some bornite, particularly that from Mufulira at a depth of 1,019 feet, is clearly anisotropic. This may be an anomalous feature in bornite, and as such has also been noted by Schneider-

[82] Schneiderhöhn, Hans, "Anleitung zur mikroskopischen Bestimmung und Untersuchung von Erzen," p. 232. Berlin, 1922.

höhn.[32] Some of it also shows a pronounced lamellar or twinning structure with alternate extinction and lighting of adjacent thin lamellae upon rotation of the stage under crossed nicols. The significance of this is not yet understood. It makes one wonder if there may not be another non-isometric form of bornite, and if bornite, like chalcocite, may be dimorphous.

The bornite occurs as: (*a*) discrete, shapeless grains of pure bornite; (*b*) stringers or veinlets of pure bornite; (*c*) apparently contemporaneous intergrowths with chalcopyrite with "mutual boundary," microstructures; (*d*) with inclusions of rounded blebs of chalcopyrite, and as similar inclusions in chalcopyrite; (*e*) as rare veinlets that traverse chalcopyrite; (*f*) intergrown with chalcocite in various microtextures; (*g*) in grains undergoing replacement by later chalcocite.

The bornite appears to be mostly contemporaneous in age with chalcopyrite but in part it overlapped and extended beyond chalcopyrite in the sequence of deposition.

Covellite.—Except for the covellite-like tarnish on bornite, the only covellite observed is in the form of minute microscopic "feathers," about 1/500 mm. in size. These are scattered along the margins of veinlets of supergene chalcocite and are characteristic of the supergene replacement of bornite or chalcopyrite by chalcocite. The covellite is supergene.

Native Copper.—This mineral was observed in only one deep underground specimen, from Mufulira at a depth of 906 feet and underlying sulphide ore. It is mostly in irregularly shaped elongated grains two or three millimeters in length. Some of the grains are euhedral; irregularly shaped blebs of chalcocite with smooth outlines are inclosed within the native copper. Neither mineral cuts the other. It is impossible to distinguish the relative ages of the two. The mineral does not resemble the usual native copper so common with oxidized copper ores. It clearly holds replacement relations to the rock silicates; straight sides of grains transgress several grains of quartz. There is no evidence that the native copper has replaced other ore minerals. The two minerals give the impression of having been formed simultaneously by direct replacement of the rock. Its interpre-

tation is puzzling. The association resembles that of the primary native copper and chalcocite in the Michigan copper deposits. It is possible that this may be hypogene native copper, whose deposition was caused locally by reaction with some substances that abstracted sulphur from the solutions, in the same way that the deposition of the hypogene native copper is considered to have been brought about in the Michigan copper deposits.

Its position in the mineral sequence is left uncertain.

Zincblende.—Only one small piece of blende was observed. It is isolated and its relations to the other minerals could not be determined.

Magnetite.—I think this mineral is detrital.

Chalcocite.—This mineral is so far the most important one, from an economic standpoint, in the sulphide deposits. It is also of great interest scientifically. It is a constituent of most of the ores and the sole copper mineral of many parts of the ore beds. It occurs as: (*a*) discrete shapeless grains of pure chalcocite; (*b*) veinlets and larger blebs of pure chalcocite; (*c*) varied intergrowths, with bornite; (*d*) as rims surrounding and replacing other sulphide grains; and (*e*) in cross-cutting ramifying veinlets which follow fractures that traverse other minerals giving rise to a mesh structure. These occurrences will be discussed later in more detail.

Some blebs of chalcocite, associated with bornite, occur in small pegmatite dikes that have been intruded in the immediate footwall of the Roan ore bed.

An interesting occurrence of chalcocite in limestone was observed at Mufulira. Specks of chalcocite are inclosed in grains of clear calcite. Other areas consist of bornite and chalcocite; the latter cuts and replaces the former. The occurrence suggests that the chalcocite metallization was brought about by hypogene solutions and not supergene sulphate waters, otherwise the calcite would not have persisted. Reaction of such solutions with the calcite would tend to form the usual copper carbonates.

The problem of the origin of the chalcocite will now be considered separately.

PROBLEM OF THE CHALCOCITE.

Unusual interest attaches to the chalcocite of the Rhodesian Copper Belt. Whether it is supergene (secondary) or hypogene (primary) is a problem of much scientific interest and of considerable economic importance. Its study also throws light on the occurrence and origin of chalcocite in general and the intergrowths of chalcocite with bornite and chalcopyrite are of more than passing interest.

As is well known, there are two kinds of chalcocite, the orthorhombic and the isometric varieties.[33] The orthorhombic is the common and stable variety and forms at a temperature below 91° C. The isometric forms above 91 ° C. but inverts to the orthorhombic form as the temperature drops below that point. If, however, chalcocite contains over 8 per cent. dissolved covellite, inversion is prevented and such chalcocite, if formed above 91° C., will remain isometric even at normal temperatures. Such isometric chalcocite is the chief ore mineral of the rich deposits of Kennecott, Alaska.[34] Isometric chalcocite, therefore, indicates a temperature of formation above 91° C., and by consequence, a hypogene or primary origin. Orthorhombic chalcocite, on the other hand, may be either the high-temperature variety that has inverted to the orthorhombic form upon cooling, or chalcocite that has been formed originally below 91° C. Thus the orthorhombic variety may be (*a*) supergene or secondary chalcocite; (*b*) hypogene chalcocite formed at temperatures somewhat below 91° C.; or (*c*) hypogene chalcocite formed above 91° C. and which has later changed over to the low temperature form. Any indication of isometric ancestry in orthorhombic chalcocite is, therefore, proof of a high temperature or hypogene origin.

The Rhodesian chalcocite is all orthorhombic, as can be determined readily under the microscope by means of polarized

[33] Posnjak, Allen, and Merwin, "The Sulphides of Copper," ECON. GEOL., vol. 10, 1915, pp. 491–535.

[34] Bateman, Alan M., and McLaughlin, D. H., "Geology of the Kennecott Ore Deposits," ECON. GEOL., vol. 15, 1920, pp. 1–80. Bateman, Alan M., "Some Covellite-Chalcocite Relationships," ECON. GEOL., vol. 24, 1929, pp. 424–439.

light with suitable equipment.[35] Some of it, however, displays features highly suggestive of an isometric ancestry and therefore of hypogene origin. Such features are to be found chiefly in the varied and illuminating types of intergrowths of chalcocite with bornite or chalcopyrite. Some of them are observable only with high power oil-immersion lenses. They are:

1. *Mutual boundary intergrowths.* The chalcocite and bornite do not cut across each other, but present curved boundaries to each other.[36] The grains are irregularly rounded in outline. Blebs of chalcocite are contained within the bornite and *vice versa*. It is impossible to say that either one is the earlier; neither replaces the other. This is a microtexture[37] common among hypogene minerals, for example, with pyrrhotite and chalcopyrite, sphalerite and tetrahedrite. It is the most common microtexture of the Rhodesian ores. It is characteristic of the hypogene chalcocite of Kennecott[38] and Bristol[39] and is common in the deep level chalcocite of Butte, Mont., for which a hypogene origin is generally admitted. This type of microtexture is never seen with chalcocite of established supergene origin, and it suggests hypogene chalcocite to me.

2. *Subgraphic Intergrowths.*—These are the well known intimate interminglings of chalcocite and bornite, in curved, hook-like lobal patterns that resemble graphic granite and the structures

[35] The isometric chalcocite remains uniformly dark under crossed nicols upon rotation of the stage; the orthorhombic chalcocite does not extinguish equally but, with powerful lighting, shows alternate lighting and darkening of adjacent grains upon rotation of the stage, and displays a diagnostic play of colors.

[36] For examples of this structure see figs. 27, 28, 29, Primary Chalcocite, Bristol, Conn., by Alan M. Bateman, ECON. GEOL., vol. 18, pp. 141–144, 1923.

[37] The terms structure, texture, and microstructure, have been so variously and inconsistently used as applied to features revealed by the study of polished surfaces, that I here suggest a general usage and one that I shall follow in this paper: The term microstructure denotes the internal structure of a single mineral grain, as revealed by the microscope or other instruments; the term microtexture denotes the fabric or pattern assumed by the individual grains of a single mineral, or by two or more minerals, as revealed by the microscope.

[38] Bateman, Alan, and McLaughlin, D. H., *op. cit.*, pp. 35–44.

[39] Bateman, Alan M., "Primary Chalcocite, Bristol Copper Mine," ECON. GEOL., vol. 18, pp. 140–147, 1923.

common in alloys (Fig. 10). The terms eutectoid and pseudo-eutectic have commonly been applied to these textures. The two minerals present mutual boundaries; they do not cut each other. About every third specimen that contains chalcocite and bornite shows this intergrowth and they are typical of most of the Roan

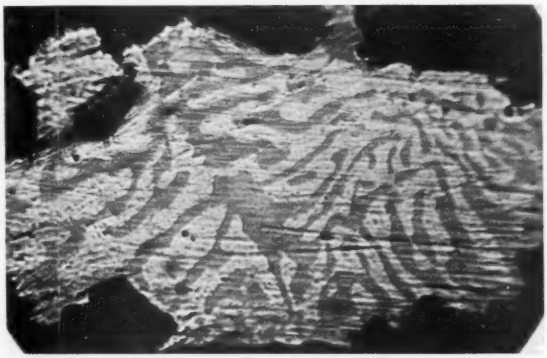


FIG. 10. Subgraphic intergrowth of bornite (dark) and chalcocite (white). Roan Antelope ore. × 440.

specimens. These microtextures are not uncommon with other pairs of minerals and are typical chalcocite-bornite patterns of the hypogene ore of Kennecott and Vigilina and of the deep level chalcocite at Butte. Their origin is disputable; some believe they represent contemporaneous deposition;[40] others that they have been formed by replacement of bornite by chalcocite.[41]

I have never seen these microtextures in chalcocite of undoubted supergene origin. Most workers agree that, regardless of whether they have been formed by contemporaneous deposition or by replacement, they are neither typical nor indicative of supergene enrichment, but are characteristic of hypogene ores, and this is my opinion of the Rhodesian examples.

[40] For example, Locke, Hall, Shore, *Trans. Amer. Inst. Min. and Met.*, vol. LXX. pp. 933–963, 1924.

[41] For example, Whitehead, W. L., ECON. GEOL., vol. 11, pp. 1–13, 1916. Lindgren, W., "Pseudo-Eutectic Structures," ECON. GEOL., vol. 25, pp. 1–13, 1930.

3. *Octahedral Intergrowths.*—These are octahedral (isometric) partings in chalcocite, observable only under high magnification (500 to 2,000 diameters) with polarized light, along which are oriented small spicules of bornite. This intergrowth is rare and was observed only after detailed search of many specimens. This microtexture differs from the well known lattice structure formed by replacement of bornite by chalcocite along bornite cleavages, described later under Number 6. There is no suggestion of replacement in it nor of inheritance of the isometric cleavage from previous bornite. Indeed, the fact that the octahedral lines of the chalcocite transgress differently oriented lamellae of adjacent twinned bornite shows that the octahedral cleavage could not be inherited from isometric bornite. The octahedral parting indicates, in my opinion, an isometric, and therefore high-temperature, ancestry for this chalcocite.

The bornite inclusions along the octahedral partings may indicate segregations during deposition or, ex-solution of bornite from chalcocite along the octahedral cleavage during cooling. Such chalcocite has never been observed from supergene deposits and I interpret it as hypogene, formed at a temperature above 91° C.

4. *Lamellar Microstructure.*—Some chalcocite shows under high magnification either with polarized light or after etching, a pronounced internal triangular pattern of blue and white chalcocite (Figs. 11, 12). This type of microstructure has been observed elsewhere and has been pictured by Segall,[42] Ray,[43] Locke, Hall, and Short,[44] Schneiderhöhn, [45] and others. Entire grains, large and small, may display this microstructure. It is rather common. The triangular pattern is brought out by minute bands of white chalcocite that are arranged along octahedral directions. The areas within the larger triangles are made up entirely of lesser triangles of blue and white chalcocite. It is clearly isometric cleavage, and there is nothing to indicate that the cleavage is in-

[42] ECON. GEOL., vol. 10, Pl. 13, 1915.
[43] ECON. GEOL., vol. 11, Pl. 11, 1916.
[44] *Op. cit.*, Fig. 3.
[45] *Op. cit.*, Fig. 122, p. 216.

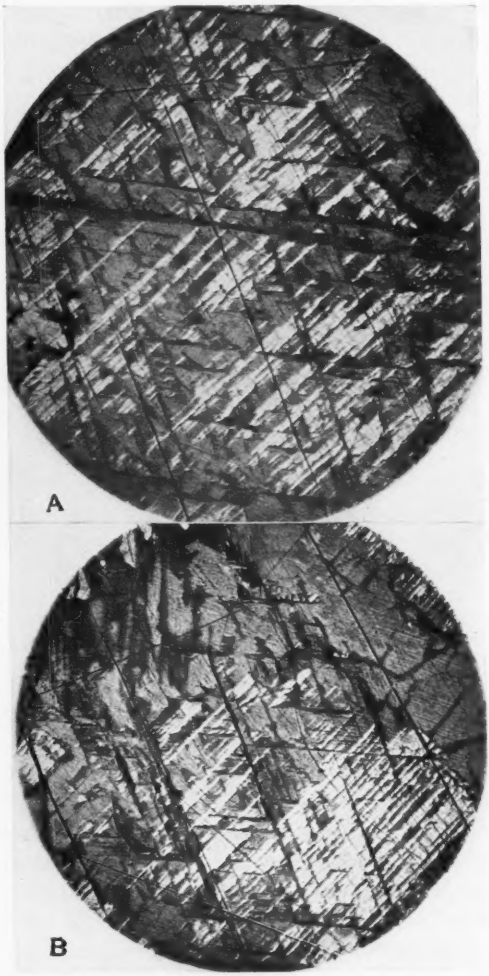


FIG. 11. Lamellar microstructure of blue and white chalcocite, showing isometric pattern. Slight rotation of the stage under x-nicols shows up the color bands more strongly in the other direction. Two different fields of the same specimen both under crossed nicols. Mufulira Mine. Drill Hole No. 1. *A*, × 230; *B*, × 190.

herited from any other isometric mineral. It is not a microstructure observed in unquestioned supergene chalcocite. Schneiderhöhn [46] considers this internal structure proof that the

FIG. 12. Lamellar microstructure of etched chalcocite; note triangular, and some rectangular patterns. Mufulira Mine, Bore Hole 1. × 110.

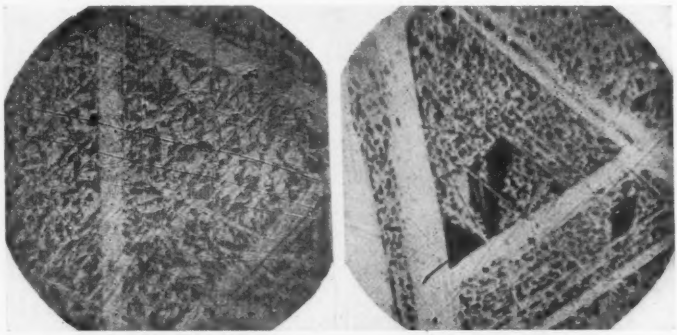
chalcocite originally had been the high-temperature isometric form, and I also interpret it for the Rhodesian chalcocite.

5. *Triangular Pseudo-Eutectic Texture.*—This rare microtexture consists of microscopic blades of chalcocite arranged in triangular pattern which inclose areas of pseudo-eutectic intergrowths of bornite and chalcocite. This is a microtexture that Schwartz [47] produced experimentally by dry unmixing during cooling of previously formed solid solutions of bornite in chalcocite, when the temperature dropped to around 200°. Schwartz [48] also found a similar microstructure in a specimen from Mufulira

[46] *Op. cit.*, pp. 213–216.
[47] Schwartz, G. M., ECON. GEOL., vol. 23, pp. 371–387, 1928.
[48] ECON. GEOL., vol. 24, pp. 443–444, 1929.

given him by Dr. Grout. His artificial structure and the natural ore from Rhodesia are here reproduced as Fig. 13. The microtextures I observed duplicate that of Fig. 13-*B*.

Schwartz [49] interprets this natural texture as a break-down of a solution of the two minerals. He thinks it suggests "eutectoid [50] deposition with chalcocite in excess forming the laths and inclosing areas of chalcocite and bornite of the eutectoid com-



A *B*

FIG. 13. Reproduction of illustration used by Schwartz (ECON. GEOL., vol. 24, p. 443, 1929). *A*, specimen from Butte, Mont., containing about 65 per cent. chalcocite and 35 per cent. bornite, heated to form a solid solution, then cooled from 300° C. to 60° C. in 69 hours. Triangular pattern of chalcocite with bornite-chalcocite intergrowth inclosed. ×615. *B*, triangular laths of chalcocite including intergrowth of bornite (dark) and chalcocite. Compare with Fig. 14-*A*. Specimen from drill hole, Mufulira Mine, Northern Rhodesia. ×615.

position." The comparison between the artificial and natural texture is striking, and in the light of our recent knowledge regarding solid solution and ex-solution, his conclusion seems a possible one. If true, it would indicate that this chalcocite was formed at a high temperature and is therefore of hypogene origin. If Schwartz's experimental temperature for unmixing should hold for natural processes, it would follow that the unmixing took place around 200° C. and that the chalcocite must

[49] *Idem*, p. 444.

[50] Personally, I do not agree with this usage of the term "eutectoid."

originally have formed above this temperature. This microtexture has never been observed in supergene chalcocite.

6. *Lattice Intergrowth.*—This is a well known microtexture that consists of intergrowths of bornite and chalcocite in a lattice-like arrangement. It has been observed or pictured by all who have studied or written about the deep-level chalcocite of Butte, Montana. It is not uncommon in the Rhodesian ores but it is

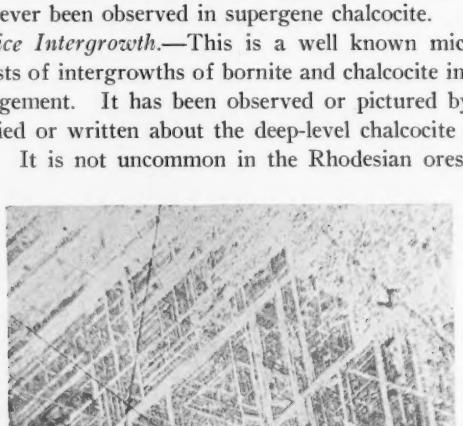


FIG. 14. Lattice intergrowth of chalcocite (white) and bornite (dark). Note triangular isometric pattern. Mufulira Mine, Bore Hole 5. × 600.

visible only with relatively high magnifications. It consists of a rather regular pattern of chalcocite in bornite and appears as if small laths or diamonds of bornite were set in a paste of chalcocite (Fig. 14). Under medium power the chalcocite merely appears off-color; the high-power oil immersion lens resolves it into distinct areas of chalcocite and bornite. The chalcocite is definitely oriented, presumably by the cleavage of the bornite. Patches of bornite may be surrounded by this intergrowth, the individual bornite particles of which become more numerous to-

ward the untouched bornite. It suggests replacement of bornite by chalcocite, controlled by bornite cleavage with bornite nucleii becoming smaller as replacement is more advanced. It is not conclusive that it is replacement, however. It may be a feature of simultaneous deposition or ex-solution from an original solid solution of bornite and chalcocite.

This intergrowth has its counterpart in the hypogene chalcocite of Kennecott, where it probably represents hypogene replacement; its similarity to that of the Butte ores has already been mentioned. Where it is distant from fractures, it is not characteristic of supergene chalcocite. I consider that in the Rhodesian ores it indicates that some chalcocite is later than bornite which it is replacing, and that it is susceptible of interpretation as either hypogene or supergene replacement, with the probability in favor of the former.

7. *Rim Pattern.* In this uncommon intergrowth in the Rhodesian ores, chalcocite encroaches upon bornite around grain boundaries so that it rims the bornite. It is clearly a replacement phenomenon. Ragged cores, only, of bornite may survive (Fig. 15). It indicates chalcocite later in age than the bornite and may represent either supergene or hypogene replacement. It is a structure characteristic of supergene replacement in many places, but hypogene replacement cannot be eliminated. I think it probably indicates supergene enrichment.

8. *Mesh Pattern.*—Occasional specimens were seen in which veinlets of chalcocite criss-cross areas of bornite or chalcopyrite in bewildering fashion, and always with a fracture in their centers. The resultant is a mesh, the threads and knots of which represent chalcocite; the inter-spaces, bornite or chalcopyrite (Fig. 16). The chalcocite veinlets may be only a few one-thousandths of a millimeter in width; they may widen until only small residuals of bornite or chalcocite remain in the inter-veinlet areas. The margins of the chalcocite are wavy or irregular and embay the succumbing residuals. Feathers of covellite, or gashes of chalcopyrite rarely margin the veinlets. This replacement is clearly controlled by the distribution of post-mineral fractures. There is a definite time break between the formation of the

FIG. 15. Rim pattern. *A*, chalcocite (cc) rimming and penetrating bornite (bn), typical of supergene chalcocite. Black is limonite. Roan Antelope Mine, Shaft No. 1. × 35. *B*, more highly magnified view (× 225) of a portion of the rimming chalcocite, showing details of replacement of bornite by chalcocite. Typical of supergene enrichment.

earlier sulphides and later chalcocite. This microtexture is absolutely typical of supergene replacement in secondary enrichment and this I interpret as supergene chalcocite.

Conclusions.—Since the Rhodesian chalcocite is orthorhombic, there are four interpretations of its origin open for consideration, namely: (1) it is hypogene, formed above 91° C.; (2) it is hypogene, formed below 91° C.; (3) it is supergene; (4) it is in part hypogene and in part supergene.

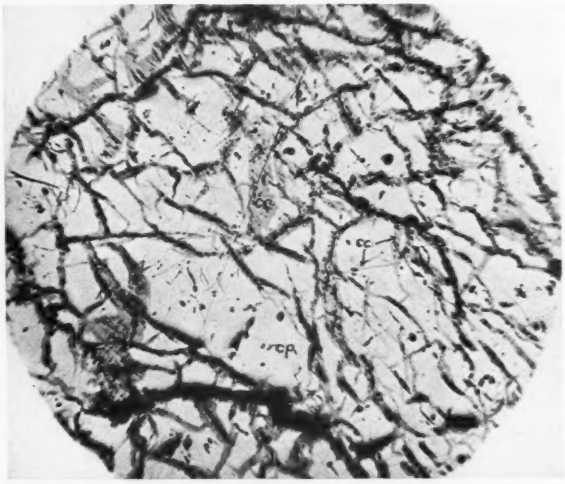


FIG. 16. Mesh structure. Chalcocite (gray) veining and replacing chalcopyrite (white) along cracks, forming a mesh. Black is limonite. Typical of supergene enrichment. Lufuba Prospect, surface. × 40.

Of the eight intergrowths described above, two indicate a supergene origin; five a hypogene origin; and one is susceptible of either interpretation but favors a hypogene origin. Furthermore, of the six that point toward a hypogene origin, three suggest contemporaneity between chalcocite and bornite, one is of doubtful interpretation, and one indicates hypogene replacement relations. The other is what Schneiderhöhn [51] considers definite proof of inverted isometric chalcocite.

[51] *Op. cit.*

The evidence, then, resolves itself in favor of a part, and perhaps the major part, of the chalcocite being of hypogene origin, and of another part being of supergene origin. The testimony of the lamellar microstructure and of the octahedral intergrowths suggests further that some, at least, of the hypogene chalcocite was formed above 91° C.; and that of the triangular pseudo-eutectic microtexture indicates, if Schwartz's conclusions can be applied to natural products, that some of it was formed above 200° C. The lattice, subgraphic, and mutual boundary microtextures also suggest a higher temperature form, if comparisons with similar microtextures found in relatively high temperature deposits elsewhere will hold.

It is concluded, therefore, that part, and perhaps the major part, of the Rhodesian chalcocite is of hypogene origin and was formed at a temperature above 91° C. or possibly above 200° C.

An interesting feature was observed in one of the specimens that exhibits lamellar microstructure. Etching revealed a veinlet of finely granular chalcocite that cuts sharply across an area of lamellar chalcocite and separates matched ends of triangles of white chalcocite lamellae. This suggests chalcocite of two ages.

There is no strangeness in the existence of chalcocite of both hypogene and supergene origin within the same deposit. Hypogene chalcocite has been shown to have been formed elsewhere and the mere presence of chalcocite can no longer be considered proof of supergene processes. The presence of hypogene chalcocite does not preclude, any more than that of bornite, the possibility of supergene chalcocite being formed at the expense of other primary sulphides. Likewise, the presence of supergene chalcocite does not preclude the possibility of hypogene chalcocite having been an original constituent of the ore, as long as other minerals were present to give rise to secondary sulphide enrichment. Indeed, it would be stranger still if there were not some supergene chalcocite present in ores that contain bornite and chalcopyrite where the conditions, as will be pointed out later, favored oxidation and some sulphide enrichment.

In setting forth this view that some of the chalcocite is hypogene, the writer realizes that his is a minority opinion, as most

of the resident geologists and others consider the chalcocite to be supergene.

Paragenesis.

Pyrite was the first mineral to form. Linnaeite preceded the other sulphides but its age relationship to pyrite is not known because these two minerals are somewhat scarce and have not been observed together. Chalcopyrite is definitely later than the linnaeite; its deposition started before the completion of the pyrite deposition and continued after it. Bornite was deposited simultaneously with the chalcopyrite but it also continued to form subsequent to the completion of the chalcopyrite deposition so that some of it cuts and replaces chalcopyrite. Chalcocite commenced to form before the completion of the bornite deposition and likewise continued to be deposited later than the bornite. Thus, some of it shows contemporaneous relations with bornite, and some distinctly cuts and replaces bornite—a relation that has commonly been observed between these two minerals in the Kennecott and Butte ores. Some change in the character of the solutions caused the later chalcocite to be deposited in part at the expense of the earlier-formed bornite. The position of the native copper is uncertain. If it is hypogene it is slightly later than the chalcocite. It may be supergene. The position of zincblende is unknown, since it was found in only one specimen. The sequence of deposition, then, disregarding linnaeite, is a diminishing ore with respect to iron and sulphur. This sequence presumably is due to a gradual change in the composition of the solutions so that the high-iron, high-sulphur minerals were deposited first, and those low or lacking in sulphur, later.

Long subsequently, when erosion removed the cover over the ore and it was revealed at the surface, oxidation and some supergene sulphide enrichment took place. Chalcocite, accompanied by minute amounts of covellite, was deposited by replacement of bornite and chalcopyrite. All the sulphides in turn succumbed to oxidation and became converted, near the surface, to native copper and oxidized copper compounds.

Supergene Sulphide Enrichment.

The field evidence lends color to the hypothesis that the chalcocite of the Rhodesian Copper Belt is a result of supergene enrichment. Oxidation has taken place, sulphides have been destroyed in the oxidized zone, climatic conditions favor it, and some drill holes disclose that bornite and chalcopyrite are more abundant at greater depths than above. These are strong arguments. Dr. Bancroft thinks [52] that all of the chalcocite, and the bornite, as well, are supergene; Dr. Gray states [53] that at Mufulira "shallow drilling indicates a secondary chalcocite zone reaching in places a depth of over 500 feet. Below this the minerals are bornite and chalcopyrite." In another place he points out [54] the possibility of hypogene chalcocite but feels that most of it is supergene and states that "if both be present, their relative proportions remain to be proved." Mr. Sharpstone states [55] that at the Roan "oxidation is usually slightly below 100 feet and no well defined (secondary) chalcocite zone has been recognized . . . ." The mine workings are as yet too few to determine with precision the field distribution of the chalcocite.

Notwithstanding the field evidence that favors supergene enrichment by chalcocite, the writer believes that his microscopic studies indicate that a part of the chalcocite is hypogene. There has been no disclosure of field evidence to oppose this idea. That some supergene sulphide enrichment by chalcocite is present in the ores is beyond question but it is the writer's belief that not all of it has been so formed.

In the field, hand specimens may be seen with sooty chalcocite coating the sulphides. These are not common, but they unquestionably indicate supergene chalcocite enrichment. Cavities remain, coated with limonite, the character of which indicates the existence there of former sulphides. The richer upper parts of

[52] Personal communications and "Notes of the General Geology of Northern Rhodesia," *op. cit.*, pp. 22, 27.

[53] *Idem*, p. 39.

[54] Geology and Ore Deposits of the N'Kana Concession, privately printed, London, 1929, p. 37.

[55] *Op. cit.*, p. 40.

some of the Mufulira drill cores, as pointed out by Dr. Gray, also suggest supergene enrichment, as does likewise the increasing predominance of bornite and chalcopyrite with depth. The latter criterion, however, must be used with caution, since primary zoning is well known to bring about horizontal and vertical changes in mineralization. The rim and mesh-work microtextures previously described further indicate supergene enrichment (Figs. 15, 16).

The environment at first glance appears highly favorable for supergene sulphide enrichment. The ores lie in a warm climate and outcrop on a peneplained surface; a long period of erosion prevailed and lowered the surface slowly; oxidation has gone on; the rocks are permeable, and prior to the present climate, the water table probably lay deep. These are physical conditions that should be propitious for extensive and thorough supergene sulphide enrichment. The wonder is that there is not more supergene chalcocite than seems to be the case.

However, there are other factors that offset somewhat the favorableness of these conditions. Extensive and thorough supergene sulphide enrichment requires, among other things, the presence in fair abundance of those minerals which, upon oxidation, yield solvents for copper. The surface generation of the solvent ferric sulphate is necessary, and it commonly is derived from ores that contain a considerable proportion of pyrite and chalcopyrite. But there is a paucity of these ingredients; the former mineral is scarce and the latter is subordinate. In this respect the Rhodesian ores bear considerable resemblance to those of Ajo, Arizona,[56] where pyrite is scarce in the primary ore and the deposit is capped by a valuable carbonate zone but a chalcocite zone is negligible or wanting. Further, the copper sulphate that is formed by the leaching action of ferric sulphate must not meet abundant neutralizers such as carbonate and to a lesser extent, feldspar, else the copper migration will be arrested in its downward journey and reactions will precipitate the copper in the form of oxidized compounds. But the Rhodesian ores do

[56] Joralemon, I, B., "The Ajo Copper Mining District," *Trans. Amer. Inst. Min. Eng.*, 49, pp. 593–609, 1914.

contain some carbonate, and its effect upon the copper solutions is seen in the abundant and widely distributed copper carbonates in the oxidized zone. Copper that becomes fixed in the form of carbonate in the oxidized zone cannot travel downward to produce supergene chalcocite at lower levels. Also, the neutralizing effect of the feldspathic host rocks is rather high.[57] The neutralizing power of the host rocks varies considerably, however. I think it is less at Mufulira than at the Roan. Consequently, greater sulphide enrichment would be expected at Mufulira than at the Roan. Further, the copper sulphate waters must meet other sulphides, since it is by replacement of them that supergene chalcocite is precipitated. Should these waters be diverted into rocks free from precipitating sulphides, the transported copper becomes dissipated and lost. The low dips that prevail in Rhodesia must allow a considerable part of the downward trickling copper waters to be diverted into the non-metallized footwall beds and thus escape precipitation of their copper. In some cases superior perviousness of beds has conducted the surface copper waters downward to great depths, bringing about local deep sulphide enrichment.

These three factors, then, the paucity of solvent-forming minerals, the relatively high neutralizing power of the host rocks, and the partial diversion of the copper waters, militate against extensive and thorough supergene sulphide enrichment. In addition, the low rainfall that presumably existed during the desert climate preceding the present one would not be conducive to extensive enrichment, although it would favor deep partial oxidation. If the oxidized zone contained less copper carbonate there would probably be more supergene chalcocite. The supergene sulphide enrichment is, therefore, not as extensive, I think, as the mere distribution of chalcocite alone might imply.

The microscopic examination indicates that some of the shallow chalcocite is clearly supergene and this material, so unmistakable in its appearance, stands in marked contrast to that which is interpreted as hypogene. This striking contrast in itself emphasizes that much or most of the chalcocite must have been formed by

[57] Tests made by Mr. William Burns, manager, N'Changa mine.

processes other than normal supergene enrichment. Again, it may be emphasized that the occurrence of some diagnostic supergene chalcocite does not imply that all the chalcocite must be supergene. The persistence of hypogene bornite (and chalcopyrite) among the highest sulphides at the Roan opposes the consideration that supergene chalcocite enrichment has been pervasive and thorough.

The impression I have formed, but which must be subject to modification when the mine workings become extended, is that the supergene sulphide enrichment is erratic and incomplete.[58] It seems to be less extensive in the Roan than in the other mines. In parts, at least, of the Mufulira it is the most complete.

From an economic standpoint, if the chalcocite is hypogene there would be a smaller diminution in grade with depth than if all the chalcocite were supergene. If the opinions expressed here be correct, the falling off in grade beneath the zone of secondary sulphide enrichment over the district as a whole will be slight. In local spots, however, where more complete enrichment has taken place, a pronounced diminution in copper content may be expected when the underlying primary ores are reached. It should be pointed out, however, that in this district, where practically the only sulphides present are copper sulphides, the drop in grade would be less in the passage to primary sulphides than in those secondarily enriched deposits where pyrite in the zone of enrichment has been converted into chalcocite. The primary ores of the Rhodesian Copper Belt, even if it be considered that they do not contain any hypogene chalcocite, are of remarkably high copper content as compared with other great disseminated copper deposits.

Mode of Entry into Host Rock.

The sulphide particles have been introduced by replacement of the minerals of the inclosing rock. They cut across, eat into and inclose residual nucleii of the rock minerals; they occur in minute threads that traverse several adjacent host minerals and have enlarged themselves at the expense of the silicates. Their

[58] By complete enrichment I mean the stage where all or practically all the original sulphides have been replaced by supergene chalcocite.

euhedral or ramifying outlines preclude the possibility that they occupy cavities not of their own making. They are accompanied, in places, by introduced quartz, carbonate, or tourmaline. Their positions clearly have been attained by the process of replacement. This is also the opinion of the resident field geologists who have had this problem in mind throughout their careful field work. Moreover, the ore minerals were introduced later than the folding of the Roan series, for sulphide veinlets were observed that cut diagonally across the shearing planes of small sharp folds.

ORIGIN OF THE ORE DEPOSITS.

The origin of these extraordinary deposits and particularly the cause of the localization of the ores, raise interesting geological problems. The unusual occurrence naturally suggested early that the ores were of syngenetic origin, thus accounting for the remarkably wide distribution laterally and for the restricted vertical or stratigraphic distribution. That this delightfully simple explanation cannot be the true one, the reader will already have inferred from the foregoing discussion.

The ores are clearly epigenetic. They were introduced subsequently to the consolidation of the host rocks and even later than the folding of the beds. They replace the rock silicates and the cementing substances. They must, therefore, have been brought in from extraneous sources by some transporting agency.

Source of Metals.—The metallic sulphides must have been introduced into the containing rocks by extremely tenuous solutions to account for the permeation of such minute openings, the character of the replacement, the widespread dissemination of the ore minerals, and the small size of some of the isolated sulphide particles. Also, the solutions must have been at quite a high temperature to have brought about the rock alteration and to have deposited such high-temperature minerals as tourmaline. A further indication of elevated temperature is the existence of the chalcocite-bornite intergrowths. The only adequate source of such solutions would be an igneous intrusion. The granite is a logical source. This is the opinion of the resident geologists and I agree with them.

The ore bodies all occur near granite intrusions and the close field association of ore and granite must be more than a coincidence. Moreover, the associations of sulphides with quartz and pegmatite, the high-temperature metamorphism of the shale near granite in the Roan syncline, and the kind of solutions that carry tourmaline, further suggest that the granite magma was the source of the metallizing solutions. It must be realized, however, that all the evidence bearing on this point is indirect.

Localization of Ore.—The puzzling problem of the localization of the ores involves two features, namely, the localization in individual beds and the localization in certain parts of the area.

The confinement of the ores to certain beds in the lower part of the Roan series is even more puzzling, when it is considered that the ore minerals occur in host rocks of such diverse chemical and mineralogical composition. This suggests that the localization in certain beds must have been controlled by physical rather than by chemical or mineralogical features.

Channelways must have existed which enabled the metallizing solutions to reach the places of sulphide deposition. I think the channelways were, in large part, the ore beds themselves and because of their permeability the metallizing solutions moved along the ore beds more than across them. The most permeable beds within the reach of the solutions were selected. This will account largely for the remarkably wide distribution and the confinement of the ore along thin beds. Support for this conclusion is found, in addition, in the local confinement of oxidation to certain beds and in the water-flows struck in bore holes and underground workings. Furthermore, one need only observe the Roan shales underground, with their prominent partings parallel to the bedding, and the water that trickles through them, to realize this. Also, the strong bedding fault [59] underlying the ore bed at the Roan acted as a channelway. Even now it carries water, and previously it allowed ready ingress of abundant pegmatitic material. There may be similar bedding faults in other mines; suggestions of them can be seen in drill cores.

[59] A thin, soft bed on the footwall of the ore, locally called "schist," which I interpret to be a bedding fault along which movement and crumpling took place during the folding of the Roan syncline.

The larger localizations of deposits in specific parts of the region involves more than permeability of certain beds. In addition, there must have been other factors that enabled the metallizing solutions to be conducted to the ore beds. If, as seems probable, the granite magma was the source of the metals, the larger localization of ore may be due to the proximity of granitic intrusions that supplied the metallizing solutions. The combination, then, of forms of intrusion and of beds more permeable than their fellows and within the reach of escaping solutions, offers an adequate explanation of the localization of the ore.

The picture that presents itself to my mind is that cupolas of granite magna, into the top of which the lighter mineralizers accumulated, ate their way upward into the troughs and limbs of synclines. Where permeable beds were intersected, the metallizing solutions streamed out of the cupolas and traveled along the permeable beds in the direction of least pressure. Then, when the conditions of temperature, pressure, and concentration were correct for precipitation, metasomatic replacement of parts of the rock, and consequent deposition of sulphides, took place. Bedding faults may also have assisted in conducting the metallizing solutions from their source to the places of ore-mineral deposition. In part, fissures may, in places, have directly tapped off the metallizing solutions from the cooling magma and conducted them to beds congenial to ingress and precipitation, or cross fissures may have diverted some of the solutions to other beds, and even, in places, may have become metallized themselves.

If the above hypothesis of origin and localization should be substantiated, it would follow that the most favorable places for ore would be where granite cuts across, or close to, permeable beds. Also, from this hypothesis, mineral zoning might be expected. High-temperature minerals might lie nearest granite cupolas, and low-temperature minerals be more remote. In this connection it would be interesting to determine if the high-temperature mineral tourmaline, which was introduced with the copper, shows any zonal arrangement with respect to the known granite cupolas; and if, for example, it is more abundant with chalcopyrite than with bornite or chalcocite.

Nature of the Mineralizers.—The metallizing solutions, as has been shown, must have been in a highly tenuous state. Their temperature must have been rather elevated, as is indicated by the presence of tourmaline. The suggestion of the former existence of isometric chalcocite would indicate a temperature over 91° C.; if unmixing of bornite and chalcocite has taken place, the temperature according to Schwartz [60] must have been over 200° C.

The solutions were rich in copper, relatively undersupplied with sulphur, low in iron, and free or almost free from arsenic and antimony. Cobalt, zinc, and probably other metals, were present in small amounts or in traces. Silica and potash apparently were not abundant. Such solutions are clearly of igneous derivation.

The mineral sequence indicates that during metallization there was a progressive decrease in iron and sulphur and a relative increase in copper; chalcocite, the copper sulphide with the highest ratio of copper to sulphur, being the last mineral deposited. This sequence indicates progressively decreasing insolubility. The mineral sequence also indicates a progression from cupric to cuprous minerals.

The relatively low sulphur content of the ores may be due either to an originally low content in the solutions or to a partial removal of sulphur through oxidation by ferric iron [61] contained in the rocks.[62] This would diminish the amount of sulphur available for combination with the copper and deposition of cuprous copper minerals low in sulphur should result.

The small proportion of iron in the ores may likewise be due to an original paucity of this element, or the original solutions may have been almost free from iron and it may have been obtained from the rocks by the solutions during their passage along the beds. If this were the case, local concentrations of dissolved iron might give rise locally to more abundant chalcopyrite and

[60] *Op. cit.*

[61] For discussion of this subject see: Bateman, Alan M., "Primary Chalcocite, Bristol Copper Mine," ECON. GEOL., vol. 18, pp. 152–164, 1923; and The Copper Deposits of Michigan, by B. S. Butler and W. S. Burbank, U. S. Geol. Surv. Prof. Paper 144, pp. 127–141, 1929.

[62] The ore beds contain little apparent ferric iron; being sediments of continental origin, they may originally have contained some.

bornite. It is not impossible that the distribution of bornite and chalcopyrite may have in part been determined by the iron content obtained by the solutions from the rocks. The iron evidently was in solution in a ferrous state.

THE SOUTH-CENTRAL AFRICAN METALLOGENETIC PROVINCE.

The Rhodesian Copper Belt, together with the adjacent Katanga copper section, constitute the greatest single copper locality in the world. There are many points of similarity between them and some of dissimularity.

The Katanga ores yield copper and cobalt; radium is produced nearby. The copper is mined from shallow oxidized deposits [63] whose ores yield about 8 per cent. copper. Low-grade sulphides are known to occur beneath the rich oxidized ores. The oxidation has been more searching and complete in Katanga than in Rhodesia and much more copper enrichment has taken place as a result of oxidation, within the oxidized zone, than in the region to the south.

Geologically, the region is somewhat similar to adjacent Rhodesia. The host rocks of the areas are the equivalent of either the upper or lower Roan series. They are, however, much more highly folded and faulted than the Rhodesian sediments. They likewise are intruded by granite and the granites of the two regions are, in all probability, parts of the same intrusive.

The Rhodesian section with its simple open folds and minor faulting represents the eroded foothill region of an ancient mountain structure. The Katanga section lies nearer the axis of this old mountain range, of which only the roots are left. Here the folds are closed and overturned; faults are numerous; and successive nappes of older strata of the Série des Mines formation are thrust above the younger Kundelungu beds.

The two regions constitute, in my opinion, a single metallogenetic province. The primary ores of both were formed at about the same time by similar processes and apparently were derived from parts of the same magmatic chamber. Both are characterized by chalcopyrite, bornite, and chalcocite, and par-

[63] With the exception of the rich sulphide deposit of the Kipushi mine.

ticularly by the rare cobalt sulphide, linnaeite. Sphalerite is sparingly present in both; pyrite is not very abundant; arsenic and antimony sulphides are rare or absent; both are low in the precious metals; quartz or carbonate is not a prominent gangue of either; and both contain tourmaline. In addition, beryl, cyanite, and magnesite occur in the Katanga ores.[64] The Katanga ores also contain other minerals not yet known in Rhodesia, particularly the uranium minerals. However, the Rhodesian Copper Belt is too little known as yet to say that similar minerals do not occur there. The occurrence in both regions of the rare mineral linnaeite establishes a definite kinship between them.

These two regions, then, constitute, a single great metallogenetic province of copper mineralization. With the further development, the dissimilarities between them may become fewer.

SUMMARY AND CONCLUSIONS.

1. The Northern Rhodesian Copper Belt will constitute the greatest individual copper mining center of the world. More than 300 million tons of over 3¼ per cent. copper have already been developed. In four to five years the region should be producing 400 million pounds of copper; in 10 to 12 years a production of over 1,000 million pounds is possible. The ore reserves may reach from 500 to 1,000 million tons. The important mines are the Roan Antelope, N'Kana, Mufulira, N'Changa, N'Changa W. Extension, Chambishi, Bwana M'Kubwa, and the Baluba and Chingola prospects.

2. The region is a slightly dissected peneplain uplifted to around 4,000 feet; the surface is flattish and bush-covered. Outcrops are few. The climate is two-seasonal—rainy and dry; the elevation offsets the low latitude; it is a "White man's country."

3. The rocks consist of an old pre-mineral basement complex unconformably overlain by the ore-containing Roan series, consisting of 3,000–4,000 feet of clastic sediments presumably of continental origin and of late pre-Cambrian age. Above this are 14,000 to 15,000 feet of generally similar sediments all of which may be of pre-Cambrian age. These beds contain 500 feet of

[64] Schoep, A., *Bull. Soc. de Belge de Geol.*, t. 37, pp. 51–56, 1927.

conglomerate considered to be of glacio-fluvial origin and probably contemporaneous in age with the "Tillite of the Katanga." The Roan series is intruded by younger granites and basic intrusives. The former are the probable source of the copper.

4. The sediments have been folded into simple pitching folds of northwesterly trend. Erosion has cut away the anticlines; parts of the synclines remain. The beds form V-shaped outcrops.

5. The ore deposits consist of one or more beds of the Roan series that have been fairly uniformly metallized with minute specks of copper sulphides that average from 0.2 to .75 mm. in diameter and are as small as 0.0001 mm.The ore beds range in thickness from 25 to over 100 feet. They occur in the synclines, and dip from 20 to 90 degrees. Their length is remarkable; the Roan Antelope ore-bed has been developed around the nose of a plunging syncline for 28,000 feet, and traced by sparse drill holes for an additional 22,000 feet. Their depth is unknown; the deepest drill hole in ore is 2,279 feet.

6. The ores are largely sulphide; the N'Changa and West Extension ore is mostly oxidized; the Bwana M'Kubwa is all oxidized. Sparse and erratic deep oxidation occurs in all the mines.

7. The oxidation extends hundreds of feet below the water level and the deep oxidation probably took place during a preceding desert climate.

8. The croppings are largely oxidized to water level. The oxidized croppings may be leached or contain oxidized copper minerals. They are susceptible of interpretation as to their previous sulphide content.

9. The mineralogy of the sulphide ores is simple. Chalcocite is the most important sulphide, followed by bornite and chalcopyrite. Linnaeite (a rare cobalt sulphide) is not uncommon and pyrite is rare. There are traces of covellite and sphalerite. Some quartz and carbonate and a little tourmaline have been introduced. The chief gangue is the inclosing rock, which consists of slightly metamorphosed argillite, arkose, feldspathic quartzites, and graywacke. These rocks have undergone some alteration as a result of the metallization.

10. Eight types of chalcocite intergrowths are described and discussed. Of these, two are characteristic of supergene (secondary) replacement by chalcocite; six suggest a hypogene (primary) origin of the chalcocite; three of these suggest contemporaneity between chalcocite and bornite. The conclusion is that the chalcocite is in part hypogene and in part supergene. The chalcocite is all orthorhombic but some of it indicates an isometric ancestry which means it was formed originally above 91° C.; part of it may have been formed above 200° C.

11. The paragenesis is pyrite, linnaeite, chalcopyrite, chalcopyrite and bornite, bornite, bornite and hypogene chalcocite, hypogene chalcocite, supergene chalcocite, and oxidation products.

12. Some supergene sulphide enrichment of (as yet) indeterminate amount has taken place. No well defined supergene chalcocite zone has as yet been delimited. The diminution in copper tenor below the supergene sulphide enrichment zone will in general probably prove small.

13. The deposits are of epigenetic origin. The sulphides have been introduced subsequently to the consolidation and folding of the rocks; they have clearly replaced the rock silicates. The probable source of the metals was the granite magma chamber.

14. The localization of the ore minerals in the sediments was probably due to the superior permeability of the ore beds.

The larger localization in certain parts of the region is thought to be due to the proximity of granitic intrusions. It is set forth that where cupolas of granite magma, into the top of which the mineralizers accumulated, ate their way into synclines and intersected permeable beds, the metallizing solutions escaped along such beds in the direction of least pressure. Then when suitable conditions obtained, deposition by replacement took place. Fissures may also have tapped off the solutions directly from the magma cupolas, or diverted them into other beds.

15. The Rhodesian Copper Belt, together with the adjacent Katanga copper region, constitute a great metallogenetic province of copper mineralization. They are linked together by many similar features of geology and ores, and the common occurrence

in each of the rare mineral linnaeite establishes a kinship between them.

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It is a pleasure to record my grateful appreciation of the information and courtesies extended to me by the officials of the various mining companies in Rhodesia and London. I wish particularly to thank Dr. Anton Gray, Chief Geologist, and Dr. D. A. Davidson, Assistant Chief Geologist, of the Rhodesian Selection Trust, and Mr. D. C. Sharpstone, Chief Geologist of the Roan Antelope Copper Mines, Ltd. These gentlemen gave freely of their time and extensive information regarding the region; Dr. Davidson spent most of his time with me during the few weeks I was in the Copper Belt. Many of the points expressed in this paper emanated from these gentlemen. I also wish to thank Dr. J. A. Bancroft, Consulting Geologist of the Rhodesian Anglo-American, Ltd., and other resident geologists of the different mines, also the officers of the Selection Trust group, for their courtesies and permission to publish this material.

LABORATORY OF ECONOMIC GEOLOGY,
YALE UNIVERSITY,
NEW HAVEN, CONN.

EDITORIAL

In our last number we made another innovation for this Journal in publishing the large supplement dealing with the origin of the famous gold deposits of the Witwatersrand, by L. C. Graton. A copy of this was sent free to each subscriber and a limited number of additional copies were printed to be made available at small cost to those who desire extra copies. We hope, in printing this 185 page supplement, that we have performed a service to our subscribers in giving them an article that is beyond the scope of ordinary journal publications.

Regardless of whether our readers may or may not agree with the conclusions expressed therein, we have been able to place before them one side of a controversial scientific problem. The Journal, naturally, being an independent publication, does not sponsor one side more than the other. We simply bring geological information and knowledge before our world-wide audience and try to advance the field of economic geology. Pertinent discussions by our readers of this controversial problem will be afforded space in our "Discussion" columns. We will welcome them.

The publication of such supplements brings to the front the desirability of being able to do so more frequently. There are occasional important papers, not entirely suitable for publication in book form, but too lengthy for inclusion in regular journals, or too costly for journals to handle. They can be satisfactorily published as supplements, provided funds are available for the extra publication costs they impose. It would be helpful to the progress of our science if a Publication Fund could be made available for just such purposes. Worthy manuscripts could then be given the distribution they deserve and would appear under the imprint of "The ———— Publication Fund." Such a fund would be a fitting memorial for some generous patron or group to establish and would constitute an inestimable benefit to our science of geology and a lasting exaltation to the founder. We hope that there may arise such a founder.

ALAN M. BATEMAN.

DISCUSSION AND COMMUNICATIONS

THE ENGELS COPPER DEPOSITS, CALIFORNIA.

Sir: The article by Adolph Knopf and C. A. Anderson that appeared recently [1] in this journal is of great interest in several respects, and especially for the conclusions the authors draw as to genesis of the deposit and for the clear conception they have of the conditions implied and the results to be expected from the theory they favor.

Basing their conclusions as to temperature of formation on the experimental work of Ramdohr on the unmixing phenomena of magnetite, ilmenite, and hematite, they derive a temperature of approximately 700° as that prevailing at the time of deposition of the ferriferous oxides and associated sulphides of the deposit. They conclude, therefore, that the conditions were pneumatolytic, and define this term as meaning "the processes whereby minerals are formed by magmatic gases acting on preëxisting or already consolidated rocks." They come out unequivocally in favor of gaseous transfer of mineral matter, and as this subject is one in which I am much interested, I should like to supplement their discussion with a few words on certain aspects of the matter.

Knopf and Anderson make the important statement (p. 33):

> The resultant ores and rocks seem unaltered to the unaided eye and have therefore that appearance of "lack of hydrothermal alteration" so commonly cited in support of the orthomagmatic origin of certain ore deposits. Rocks in which actinolite, biotite, and plagioclase have formed metasomatically are bound to look fresh and unaltered; in fact, it is characteristic of pneumatolytically altered rocks to have that appearance.

This statement deserves the fullest attention and reflection. I believe that failure to recognize these facts, so clearly stated here, is to be observed repeatedly in discussions in which these matters

[1] ECON. GEOL., vol. XXV., No. 1, Jan.–Feb., pp. 14–35, 1930.

are involved, and that this has led to baseless inferences. Examination of the minerals of lithophysæ and similar aggregates should point to the truth of the statement quoted. In lithophysæ the question of whether additions of mineral matter have or have not been made is not the immediate point to be considered; the significant feature is that such minerals as alkaline feldspars, quartz, tridymite, olivine and other ferromagnesian silicates, iron oxides, and other minerals, of perfectly fresh character, have crystallized under conditions where the presence of a considerable concentration of volatiles is indicated. Moreover, in plutonic bodies in general, but especially in those of high silica content, and above all in many of the pegmatites, the last stages of consolidation must generally have been carried out in the presence of escaping volatiles without causing those destructive effects of which evidence is sometimes demanded. The idea, often expressed or implied; that magmatic gases necessarily exercise destructive action, which should be readily recognizable, upon the ordinary rock-forming minerals, is apparently based upon the disintegrating effects observed when these gases escape from fumaroles at the surface, where a far different set of conditions prevails, not applicable to those at depth.

There is evident at times some misunderstanding of the nature of the processes involved in gaseous transfer, and perhaps the reluctance shown by some in accepting the idea may be based partly upon misapprehension. The idea seems to be prevalent that when transportation of mineral matter by magmatic gases is favored the solvent agent is to be regarded as predominantly water vapor. This idea apparently survives from a period when it was actually urged, when the nature of the magmatic gases was less well known and the chemical principles governing their behavior was less well understood. It belongs in the same category as the attempts to determine, by theoretical reasoning, in exactly what combinations gases are present in the magma: a problem which, from its nature, is hopeless of solution except in the most general terms, as the combinations must vary from one magma to another, and from one period to another in the same magma. The present attitude with regard to water vapor is to

look upon it as an important agent in sweeping away products of reaction, but to attribute to it little solvent power; in fact, to ascribe to it rather a precipitating influence under certain conditions. Later students who favor gaseous transfer and have directed their attention to the nature of the gases given off by magmas and the probable chemistry of the processes, place the emphasis as regards the effective agents very differently. They lay stress upon the presence of hydrochloric and hydrofluoric acids especially, and the generally easy volatility of the inorganic compounds of these halides.

Furthermore, the principles established in physical chemistry in recent years find important application in throwing light upon the problems involved. An exposition of these principles applied directly to an explanation of ore deposits has lately appeared in a very important publication by E. G. Zies.[2] This is practically the only publication in English in which these matters are fully discussed by a competent authority, and is one of the best that has appeared in any language. It is clearly expressed and is free from the unnecessarily formidable methods of representation adopted by some authors. Attention may be directed to the application made in it of the principle of mass action, the theory of incomplete reactions, the effect of changing conditions in displacing equilibrium, and the favoring effect produced by dynamic conditions in bringing about important accumulations. Careful study of this work should do much to clear away a number of misunderstandings, and its influence should be far-reaching.

Another statement by Knopf and Anderson (p. 31) again emphasizes the fresh appearance of the metasomatically altered rock, and may serve as an introduction to another important point. It reads:

> Similar ore has recently been cut by diamond drilling 500 feet below the 13th level. This, the deepest ore yet found, is a thoroughly fresh-looking granitic rock carrying disseminated chalcopyrite. . . . The ore is a biotitized orthoclasized quartz diorite which has probably been hornblendized and into which magnetite and chalcopyrite have been intro-

[2] E. G. Zies, "The Valley of Ten Thousand Smokes," *National Geogr. Society*, Contributed Technical Papers, vol. 1, No. 4, 1929.

duced. It must be emphasized that the metasomatic alterations by which the quartz diorite was transformed to ore are essentially like those by which the hornblende gabbro was altered, namely, biotitization, recrystallization of the large pyrogenic plagioclase feldspars to fine-grained mosaics of andesine-labradorite, and the introduction of magnetite, chalcopyrite, bornite, titanite, and apatite.

The feature to which it is desired to call attention is the introduction of chalcopyrite, magnetite, and other minerals as disseminations in a fresh-looking granite. On another page (p. 22) they speak of a gabbro which "contains hornblendic blebs in which there is a little disseminated chalcopyrite, and it is by no means easy to tell whether these blebs are the results of liquid-magmatic segregation or of postmagmatic hornblendization." They believe, however, that the evidence indicates "that the gabbro magma contained some copper sulphide, but the amount was insufficient to produce a notable metallization, which was of much later origin."

They recognize, therefore, that later introduction of sulphides may produce results in the way of disseminated blebs which can hardly be distinguished from magmatic segregations; and I think this inference is supported by innumerable instances in which wall rocks adjacent to veins have been impregnated with sulphide minerals in disseminated form without revealing evidence of the channels by which they have entered. In the controversies that have been carried on in regard to such ore bodies as those of Sudbury the supporters of the orthomagmatic theory of origin have laid the greatest emphasis upon the fact that masses of the intrusive remote from ore bodies contain disseminated sulphides having every appearance of being original constituents of the magma. While their conclusions may be true in large measure, the principal criterion by which they seek to establish it loses much of its force in the light of similar phenomena found under circumstances which point to a later introduction of sulphide minerals into solid rock.

Before a decision can be reached in such cases among the conflicting claims of magmatic segregation, gaseous transfer, and hydrothermal transportation, it will be necessary to arrive at an

understanding of the general principles involved in each process and the criteria by which the results may be discriminated.

In addition, it seems desirable to realize that in many instances all three processes may proceed simultaneously in different portions of the same deposit, or at different times in the same portion. Evidence that one process has been operative does not necessarily exclude other processes. We may conceive the reasonable hypothesis that under certain ideal conditions the emplacement of a large body of magma is followed by the segregation of sulphide compounds by gravitative liquation or otherwise within the liquid mass. At the same time the evolution of magmatic gases carries volatile compounds outward to the exterior shell of the intrusive body, and into the wall rock. These volatile compounds of the heavy metals are accompanied by such potential precipitating agents as H_2S and H_2O (or the elements from which they may be formed), which become effective in deposition when cooler regions are reached or when the original acid character of the emanations is modified by reaction with the walls and by dilution with interstitial solutions. In the early stages subsequent to emplacement, before the original heat is greatly dissipated, the gaseous emanations may extend to a great distance from the hot source, but eventually condensation will follow and hydrothermal solutions will be the result. Gradually, as cooling proceeds, the limits to which the gases penetrate will be diminished, and the hydrothermal solutions will close in around the focus, until eventually only a small interior portion of the intrusive will continue to give off the gases that act as propulsive agents for the hydrothermal circulation, and finally even this ceases. In these later stages those portions of the deposits originally formed by magmatic segregation and by deposition from gases will, unless blocked off, be acted upon by hot aqueous solutions, which now have probably assumed an alkaline character, and these will produce important effects in transportation and recombination of mineral compounds, and will impress upon the whole deposit more or less thoroughly their own particular stamp. In many instances these final processes may obliterate nearly or

quite all evidence of what has gone before, and of the original writing on the palimpsest no recognizable evidence may remain.

CLARENCE N. FENNER.

GEOPHYSICAL LABORATORY,
CARNEGIE INSTITUTION OF WASHINGTON.

ORIGIN OF CHROMITE DEPOSITS.

Sir: It is with great interest that I have studied Mr. Lloyd W. Fisher's thesis on the above subject,[1] a subject which has been somewhat neglected in the past. As a record of wide research into the similarities and dissimilarities between chromite deposits in various parts of the earth the thesis should prove of great future value.

Mr. Fisher has labored under the disadvantage of not being able to study many of the occurrences in the field and furthermore of having, in the case of the Great Dyke of Southern Rhodesia at all events, specimens from a very limited locality upon which to base his conclusions.

On pages 708–709 of the paper the author dismisses my suggestion as to the possible cause of the chromite in the Great Dyke occurring in layers, as untenable. I fully agree with him, as further work in the field and in the laboratory has caused me to revise the opinion expressed in Short Report No. 23 of the Southern Rhodesia Geological Survey. My latest views will be found in a bulletin of the Survey dealing with the same deposits and now in press.

I must, however, disagree with the statement that the Great Dyke is "younger than the rocks of the Bushveld Complex" (p. 706). We have no evidence suggesting such an age relation, all the available evidence being in favor of the supposition that the two intrusions were, more or less, contemporaneous.

It is hard to understand how the chromite of the seams, as distinct from what might possibly be secondary chromite in the serpentine wall rocks, can be considered to be of *late* magmatic origin, that is, later than the silicates of the wall rocks. There

[1] ECON. GEOL., vol. 24, 1929, Nov. pp. 621–721.

is, definitely, no evidence of replacement of bands of peridotite or pyroxenite (now serpentinized or not serpentinized as the case may be, in varied occurrences) by chromite. The chromite of the seams is commonly euhedral, the crystals often being of large size, with faces several millimeters across.

Rather must it be considered that the bulk of the chromite of the Great Dyke was deposited contemporaneously with the ferromagnesian silicates (olivine, enstatite and diopside) now found, fresh or serpentinized, associated with it. When making this statement I refer to the basic mass as a whole, as it is my belief that the various seams of chromite, with their serpentine-rock or enstatite rock walls, were deposited during gravitational differentiation of the basic magma. In other words if Mr. Fisher will interpolate a period of crystallization of the chromite between his (1) early magmatic and (2) late magmatic (page 692) I believe that he will be able to cite the deposits under discussion as the typical example of such a period.

It is of interest to note that the late P. A. Wagner, a few weeks before his lamented death, placed on record (Transactions of the Geological Society of South Africa, 1929) the discovery of stichite at the Amianthus Mine, Transvaal; particularly so in view of the fact that Mr. Fisher's description of the Tasmanian specimens of this mineral fits the rock as found in this country with great exactitude.

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REVIEWS

Handbook of the Geology of Great Britain. A compilative work. Edited by J. W. Evans and C. J. Stubblefield. Pp. xii + 556, illus. 67. Thos. Murby & Co., London, 1929. Price, 24s.

This volume is a revised edition of the treatise on the Geology of Great Britain that appeared in the "Handbuch der Regionalen Geologie" in 1917. The discussion has been brought up to date and is now the most complete summary of the geology of England, Wales and Scotland available. It contains a description of the physical geography of England and Wales by A. Morley Davies, and of Scotland by J. W. Gregory. The known earthquakes that have occurred in Great Britain are listed and briefly described by C. Davison. The stratigraphy of the pre-Cambrian group is treated by W. W. Watts and Gregory, of the Cambrian and Ordivician systems by Watts, of the Silurian System by O. T. Jones, of the Devonian System by Evans, of the Carboniferous System by P. F. Kendall, E. J. Garwood and W. B. Wright, of the Permian System by H. C. Versey, of the Triassic and Rhaetic Systems by L. Richardson, of the Jurassic System by Davies, of the Cretaceous System and the Tertiary rocks by P. G. H. Boswell. The Quaternary period, including the glacial deposits and glacial erosion, buried forests, peat deposits, etc., is discussed by G. Slater, and the Stone Age and its relicts by H. Dewey. The intrusive igneous rocks of Ordovician, Silurian, Devonian, Carboniferous, Permian, and Tertiary age are briefly described by A. Harker. An appendix by John Parkinson, dealing with the geology of the Channel Islands, completes the text. Comprehensive bibliographies are scattered through the volume and an index of authors, fossils, place names, rock names and the names of stratigraphic units, ends it. This index covers 24 pages of three columns each.

The volume is a compendium of facts concerning the geology of Great Britain and a dictionary of terms used in describing it, also a guide to the literature on the subject. It is indispensable to any one interested in the geology of this interesting portion of the earth's crust. It is well printed and sufficiently well illustrated to meet the needs of the reader.

W. S. Bayley.

Das Kali, Teil II, By ERNST FULDA (together with W. GROPP, O. KRULL, and P. KRISCHE). Pp. 400, text figs. 109, map. Ferdinand Enke, Stuttgart, 1928.

This is a companion to the earlier volume by Krische, which covered: (1) the history of the potash salts and the development of the German potash industry; (2) the distribution of potash in nature. The present volume follows the long out-of-date but well known monograph, Festschrift zum Eisenacher Bergmanstag, by Beyschlag and Everding, 1907, and covers a description of the potash minerals, their formation in nature, the geology of potash deposits, mining, manufacture, and agricultural and industrial use of potash salts.

The text is well and interestingly written, and in the portions read by the writer the German is relatively easy. The paper, illustrations, and type are good. The book will make a valuable text and reference book on potash salts.

DONALD C. BARTON.

Structure of Typical American Oil Fields. A Symposium, etc. Vol II, 1929. Pp. xxii + 780. Illus. 235. *Amer. Assoc. Petr. Geol.,* Tulsa, 1929. Price, $6.00.

The first volume of this symposium was noticed in these pages a few months ago (ECON. GEOL., Vol. 24, p. 339). This second volume follows the plan of the earlier one of which it is a continuation. Forty new papers by forty-five authors discuss typical fields in Colorado, Illinois, Montana, New York, Pennsylvania and Wyoming, and fields in Arkansas, California, Kansas, Louisiana, Oklahoma, Texas and West Virginia that had not been discussed in the first volume. The two volumes taken together describe all types of oil fields that are at present known to occur in the United States and the adjacent parts of Canada and Mexico. Most of the descriptions are clearly written and well illustrated.

The special feature of the new volume is a critical essay by F. G. Clapp on the rôle of geologic structure in the accumulation of petroleum, based very largely on the facts developed in the various papers in the two volumes. The essay summarizes and correlates the conclusions of their various authors with the view of showing that "the accepted relationships of oil and structure prevail universally, subject to the control of other fundamental criteria. . . . Every so-called 'exception' is found to clinch the structural principles more firmly than before . . . ."

Unquestionably the two volumes should be in the library of every structural geologist as well as of every petroleum geologist. The book is well printed, well illustrated and well bound.

W. S. BAYLEY.

Die Rumänischen Erdöllagerstätten. By KARL KREJCI-GRAF. Pp. 140, illustrated. Ferdinand Enke, Stuttgart, 1929. Price, 15 marks.

The author presents in a very clear fashion the essentials of the geology of the Rumanian oil deposits.

The oil-fields of Rumania are closely associated with the overthrust masses of the southeastern Carpathians and are thus related to the Galician fields. Whether eventually the two zones will prove to be continuous is not known at the present time.

The sedimentary rocks involved range in age from Upper Cretaceous to Pliocene and since crustal movements began in the Oligocene and continued through the Pliocene, there is presented a bewildering array of structures and of facies. Salt deposits are associated with the series and are believed to be of Upper Oligocene age (Aquitanian).

In East Rumania, the major part of the oil lies in the *decke* zone, where at least traces are found in formations of all ages and in all facies. Residues are particularly noticeable in beds of Upper Oligocene age, which are rich in plankton and fish remains and are noticeably lacking in the Eocene beds which are rich in bottom-dwellers. Little oil is found associated with salt masses.

In South Rumania conditions are reversed and little oil is found in the *decke* zone while the great fields are associated with great salt masses which have been subjected to lateral thrusts with the formation of all types of structure from simple anticlines to diapir folds. In this region oil lies in the Pliocene beds, unlike the eastern fields, where it is produced mainly from the Oligocene.

Having such an assemblage of beds and facies, the author presents a study of the region which is calculated to throw much light on the origin of the oil. From the presence of bituminous residues and as a result of a study of the life involved, the author concludes that the oil had its origin in the Oligocene shales from which it migrated into other beds. No great distance separates the supposed source beds from the reservoirs in any case.

The specific conclusions reached are used in a general discussion of the origin, migration and accumulation of oil which, in the opinion of the reviewer, warrants careful reading whether one is interested in Rumania or not.

A very complete bibliography is appended and the book is well indexed. Altogether it is a most satisfactory discussion of a type which is needed for many other regions, not excluding the United States.

W. V. HOWARD.

UNIVERSITY OF ILLINOIS,
URBANA, ILLINOIS.

BOOKS RECEIVED.

By

C. B. HUNT.

The Granby Anticline, Grand County, Colorado. By T. S. LOVERING. Pp. 5, pl. 1. U. S. Geol. Surv. Bull. 822–B, 1930 (Mar.). Price, 5 cts. Stratigraphy, structure.

Mining Methods and Practice in the Michigan Copper Mines. By W. R. CRANE. U. S. Bur. of Mines Bull. 306, 1929. Pp. 192, figs. 147. Price, 60 cts. Mining methods, character and occurrence of the ore, mining practice and costs.

Flow of Gases through Beds of Broken Solids. By C. C. FURNAS. U. S. Bur. of Mines Bull. 307, 1929. Pp. 143, figs. 79. Price, 30 cts. As a result of 258 separate sets of data, conclusions are reached that enable the engineer to predict with fair accuracy the resistance offered to gaseous flow by a bed of broken solids of sized material.

Annual Report of Director, U. S. Bureau of Mines, for year ending June 30, 1929. Pp. 63, 1 chart, 2 figs. Price, 10 cts.

Economics of New Sand and Gravel Developments. By J. R. THOENEN. U. S. Bur. of Mines Econ. Paper 7, 1929. Pp. 60, figs. 23. Price, 15 cts. Economic factors; nature of deposits; markets; methods of excavation. Bibliography of 225 titles.

Surface Water Supply of the United States, 1925. Pt. I., North Atlantic Slope Drainage Basins. Pp. 268, figs. 1. Water Supply Paper 601. Price, 30 cts. **Pt. II.**, South Atlantic Slope and Eastern Gulf of Mexico Basins. Pp. 107. Water Supply Paper 602. Price, 15 cts. **Pt. III.**, Ohio River Basin. Pp. 343. Water Supply Paper 603. Price, 40 cts. **Pt. IV.**, St. Lawrence River Basin. Pp. 179. Water Supply Paper 604. Price, 25 cts. **Pt. V.**, Hudson Bay and Upper Mississippi River Basins. Pp. 179, figs. 1. Water Supply Paper 605. Price, 25 cts.

Upper Colorado River and its Utilization. By R. FOLLANSBEE. Pp. 395, figs. 5, pl. 13, maps 9. U. S. Geol. Surv., Water Supply Paper 617, 1929 (Feb. 1930). Price, 65 cts.

Geological and Mining Features of the Tarkwa-Abosso Goldfield. By O. A. L. WHITELAW. With Appendix giving Report on the Microscopical Examination of the Rocks, by N. R. JUNNER. Pp. 45, pl. 12, maps. Gold Coast Geol. Survey Mem. 1, 1929. Price, 5 s. Stratigraphy, structure, genesis of the interesting gold ores that resemble the Witwatersrand and are considered of placer origin.

SCIENTIFIC NOTES AND NEWS

Chester K. Wentworth, geologist for the U. S. Engineer Office, Kansas City, Missouri, is spending the summer in the examination of dam sites in the Missouri River Basin.

F. H. Moffit, of the U. S. Geological Survey, is to lead a party in the investigation of the Kantishna region, Alaska.

J. B. Mertie, of the U. S. Geological Survey, will survey this summer an unmapped tract in Alaska north of the Yukon and south of the Porcupine River.

A. C. Lane is nominated for president of the Geological Society of America.

Frank L. Hess is now in South America.

J. E. Spurr has returned to his home in New Rochelle, N. Y., after spending the winter with his family in Florida.

S. R. Capps, of the U. S. Geological Survey, will carry on a survey during the summer in the vicinity of Broad Pass and the head of the Chulitna River, Alaska, and will investigate the mineralized areas of that region.

B. D. Stewart, supervising mining engineer, Juneau, Alaska, is making an investigation for the U. S. Geological Survey in the vicinity of the Taku River, east of Juneau, in the newly discovered lode areas of that district.

E. L. Bruce, Miller Memorial Professor of Geology at Queen's University, Kingston, Canada, sailed on May 23, to spend the summer chiefly in Finland.

M. I. Goldman, of the U. S. Geological Survey, is at present in Europe.

C. D. Avery and C. E. Dobbin, of the Rocky Mountain Division, U. S. Geological Survey, are at work on a land classification of coal and oil lands in Alabama, Mississippi, and Louisiana.

Lucien Eaton is spending two or three months in the Rhodesian Copper Belt.

Arthur L. Hawkins has resigned his position with the Transcontinental Oil Company to open an office as consulting geologist in the Continental Oil Building, Denver, Colo.

Charles H. Behre, Jr., has left the Geological Department of the University of Cincinnati to take an associate professorship of economic geology at Northwestern University.

Charles W. Merrill has been appointed chairman of the recently formed State Mining Board of California.

Irving B. Crosby, of Boston, Mass, is to attend the World Power Conference in Berlin next June.

Robert Bedford, of Grass Valley, California, has gone to Russia to investigate various gold mining areas for the Soviet Republic.

H. W. C. Prommel, of Denver, Colorado, has taken a position with the Soviet Government as chief geologist in non-ferrous minerals.

Mary G. Keyes, formerly of the Geophysical Laboratory, Washington, D. C., has opened a laboratory for chemical analysis at 1512 Thirty-first Street, Washington.

Frederick G. Clapp has returned to New York, and while retaining his office at 50 Church Street, has established a working office at Bronxville, N. Y.

John A. Burgess is now in San Francisco representing Mayflower Associates and other companies.

A. W. Hahn, of Salt Lake City, Utah, has been spending some time in Mexico, and has now gone to Russia to act in a consulting capacity for the non-ferrous metal trust.

George E. Cole, Chief Inspector of Mines for Manitoba, Canada, is to be head of a new department to control the mineral resources of the Province.

F. W. Maclennan, general manager of Miami Copper, is spending four months in a trip to South Africa.

Charles A. Mitke left from San Francisco on May 14 for Mount Isa, Queensland, Australia.

The Shell Oil Company has removed its headquarters to the Shell Building, San Francisco, Calif.

The U. S. Geological Survey is continuing this year topographical mapping in the vicinity of Ketchikan, Alaska, under the direction of R. H. Sargent.

James R. Finlay and Arthur Notman have removed their offices to 40 Wall Street, New York City.

At the Champion Reef gold mine, Mysore, India, a new ore body has been cut on the 71 level, at a depth of 6,700 feet.

The age of the producing horizon in the deep oil wells of Texas is now known to be Ordovician, according to the State Bureau of Economic Geology.

The recently published 20-volume index (336 pages) of ECONOMIC GEOLOGY for 1905 to 1925, compiled by J. M. Nickles, may be obtained for $3.00 from W. S. Bayley, University of Illinois, Urbana, Ill.

ERRATA

For Supplement to Number 3, vol. 25, May, 1930.

Hydrothermal Origin of the Rand Gold Deposits by L. C. Graton,

Part I.

Page	*Line*	
20	13	"dilemma."
23	1	dash should be final parenthesis.
26	19	"coarseness as" should be "coarseness of."
28	21	"Of" should be "Or."
36	31	"necessary."
43	7	"of requisite" should be "in requisite."
51	28	semicolon should be comma.
55	18	"exceedingly."
85	4	"quartzites."
88	4	after "footwall" and also before "argillaceous" insert line of dots, to indicate words omitted.
88	5	dash should be line of dots, to indicate words omitted.
103	7	from bottom — "richness."
106	18	"rests"
141	19	"goes" should be "does."
141	22	"its does" should be "it goes."
145	23	"fortuitous"
148	23	"minerals"
154	9	from bottom — "neighborhood"
168	18	"deduced"
179	7	"energy-advantage."
180	15	"enlargement."

(Please remove and insert in Supplement to Number 3.)